NLSRT Memo No. 32

NRAO INTERNAL DOCUMENT

PROCEEDINGS OF A

GREEN BANK WORKSHOP

December 2-3, 1988

WARNING. People who contributed to this document have not had an opportunity to review or correct their contributions. These Proceedings should be considered working documents only, hopefully providing a framework for further discussions.

Introduction

The 300 ft telescope collapsed during the night of November 15, 1988. Within days thereafter, Senators Byrd and Rockefeller requested a briefing from the National Science Foundation providing (1) the cause of the collapse and (2) what NSF's replacement plans were. A meeting was held in then-Majority Leader Byrd's office on November 28, 1988. In attendance were Erich Bloch and Ray Bye of NSF; Bob Hughes, Paul Vanden Bout, and George Seielstad from AUI-NSF; and Senators Byrd and Rockefeller, plus two aides. The cause of the telescope's collapse was explained to be still unknown, but the investigations to determine it were described. Most of the discussion at the meeting centered on a replacement telescope.

NRAO made clear that it would be proposing to NSF a replacement telescope. Exact specifications were not stated, pending input from the scientific community. We announced that invitations to attend a planning meeting in Green Bank had been sent to several radio astronomers. Director Bloch stated that any proposal to NSF would be evaluated within the context of the overall scientific needs of the nation and that these evaluations proceeded on an unspecified time schedule. Senators Byrd and Rockefeller clearly expressed that they hoped for a firmer commitment and a definite timetable. (Appendix A is a copy of a news release they issued describing their views of the meeting.) Bloch agreed that he and the Foundation wanted to find a way to cooperate.

The main result of the meeting was to insist upon specifics: What kind of telescope does NRAO want? How much will it cost? How quickly can it be constructed? Is the NSF committed to funding it, under assurance that the funds would be add-ons to existing commitments? A second meeting was scheduled for January 5, 1989, by which time answers to these questions are expected. NRAO hopes to provide its plans to NSF in advance of that date.

Planning Meeting

Fifty-six people attended a planning meeting held in Green Bank, WV on December 2 and 3, 1988 (List of Attendees in Appendix B). In addition, ten people who were unable to attend (listed in Appendix C) submitted contributions (assembled separately). The purpose of the meeting was to find from the users what science should guide the design of a replacement telescope. To stimulate discussion, science was divided into eight categories, and a spokesperson for each category assigned to initiate discussion of it. The categories and discussion leaders were:

Single Dish Continuum	Jim Condon
Galactic Neutral Hydrogen	Jay Lockman
Extragalactic Neutral Hydrogen	Rick Fisher
Pulsars	Don Backer
Stellar Emission	Bob Hjellming
Spectroscopy	Al Wootten
Highly Redshifted Spectral Lines	Bob Brown
VLBI	Ken Kellermann

These dicussions were sandwiched between a report by Ken Kellermann on "A Very Large Dish (VLD) Radio Telescope," the outcome of a study initiated in 1988 to consider the status of single-dish astronomy, and a summary report by Rick Fisher on "Design Concepts and Compromises."

Following the introductions by topic and considerable general discussion, participants were split into working groups whose charge was to summarize in writing the scientifically most exciting questions in their sub-disciplines and to specify the technical requirements of an instrument to address these questions. Participants were reminded that major telescopes have lifetimes of decades, so that the needs of future generations of astronomers, to the extent they can be foreseen, had to be taken into account. These working groups and their leaders were:

Pulsars and Stars	Don Backer
Neutral Hydrogen Galactic, including Zeeman Effect Extragalactic OH	Carl Heiles
Spectroscopy Comets Galactic Extragalactic	Al Wootten
Continuum Radiation Continuum mapping/source surveys VLBI Galactic Background Radiation Microwave Background Radiation Source Variations	Jim Condon

Attendees chose the group to which they wished to contribute. Each group produced a **DRAFT** report, and these are collected at the end of this document. THE GROUPS HAVE HAD LITTLE OPPORTUNITY TO CHECK OR CORRECT THEIR REPORTS. THESE MUST BE CONSIDERED INTERNAL DOCUMENTS ONLY.

The meeting concluded with verbal presentations by the leaders summarizing the conclusions of their groups. A general discussion also ensued.

Summary of Technical Requirements

Only the full reports do justice to the contributions by the participants. A capsule summary, though, for quick reference, is presented in Table I. In Figure 1, we plot aperture diameter as a function of frequency as called for by the different disciplines. The diameter specified is a representative measure of collecting area desired; it need not refer to a single aperture only.

Points of General Agreement

1) Any new telescope must be world class. That is to say, it must expand parameter space in some dimensions, offering capabilities unique in the world. In this connection, a listing of other similar telescopes is in order.

Freq > 100 GHz	IRAM, 30m
Freq > 50 GHz	Nobeyama, 45m
Freq < 50 GHz	Bonn, 100m
Freq < 23 GHz	Phased VLA, ~125m

Freq < 10 GHz	Upgraded Arecibo, 210m
Freq < 1.4 GHz	GMRT, 34 x 45m

2) The new telescope cannot be considered an adequate replacement for the 300 ft telescope unless it offers at least equivalent collecting area at frequencies < 5 GHz. The minimum diameter is therefore ~100m.

3) The telescope must point at least as far south as the Galactic Center and must have tracking capability. Since its mount (or mounts) will almost certainly be alt-az, the two requirements overlap. The preference is for sky coverage all the way to the horizon; the minimum acceptable coverage would be to elevation ~10°.

4) Interference is radio astronomy's severest problem, and one growing ever worse. Telescope designs must consider ways to minimize rfi. At the same time, the National Radio Quiet Zone is Green Bank's greatest advantage.

5) Considering sites other than Green Bank is pointless.

Other Issues Discussed

1) Filling Factor. Should all the collecting area be in a single aperture or distributed over several?

2) Frequency Range. Should the telescope limit observations to frequencies less than about 5 GHz and provide for those frequencies the greatest collecting area a given amount of money can buy? Or should observations at higher frequencies be possible, even if collecting area must be sacrificed? Can some combination telescope provide the best of both worlds?

3) The Crystal Ball. Given that interference is worsening and is propagating its damage up from low frequencies to high, should a new telescope include high-frequency capability in case low frequencies some day become unobservable?

4) Interference. Interference, stray radiation, and standing waves generated by multiple reflections are all serious limitations. Do offset feed structures solve them? Can they be built if the diameter is ~100m? Is their cost significantly greater than that of a conventional reflector? Can minimal blockage apertures suffice? Can clear portions of a blocked aperture be utilized effectively? Can post-detection analysis remove interference?

5) Atmospheric Conditions. How does the Green Bank environment affect observations at various frequencies? For what fraction of the time are various observing frequencies possible?

Resolution of these (and other) issues is a matter of opinion. Therefore, their discussion has been separated from a facts-only report of the meeting by incorporating them into Appendix D. Entries there are from Alan Bridle, Tim Cornwell, and George Seielstad. Others who wish to have contributions included are welcome to submit them.

Schedules and Costs

The only estimates were provided by Ken Kellermann. These must be considered extremely preliminary approxmations.

Tentative Schedule

End 1988	Telescope concept decided (Aperture size, filling factor, frequency range)
End 3/89	Reflector type selected (Offset feeds, minimum blockage, shaped or standard parabola)
End 1989	Design sufficient to submit for study by engineering firms
End 1990	Design finalized to point where firm bids can be prepared
1991	Site work and fabrication begin
1992	Erection begins
End 1992	Site work completed
End 6/93	Fabrication completed
End1993	Erection completed
1994	Outfitting, testing, final adjusting

Approximate Costs

Diameter	Wavelength Limit	Cost	Source
100m	1.5 cm	$50M	Krupp for Germany site
100m	1.5 cm	$39M	Krupp for GB site
330 ft	1.5 cm	$50M	NRAO/300 ft(1969)
70m	0.7 cm	$45M	NRAO 65m (1972)
70m	?	$70M	NRAO VLBA
300 ft	6 cm	$15.8M	Fisher
450 ft	6 cm	$40M	NEROC
300 ft	6 cm	$12M	RSI (elevations>30°)
450 ft	6 cm	$35M	NRAO/300 ft (elevations>30°)
450 ft	6 cm	$47M	NRAO/300 ft (full sky coverage)
100m	2 cm	$59M	NRAO VLBA
100m	1.3 cm	$80M	NRAO VLBA
100m	3 cm	$91M	JPL (space-tracking capabilities)

Costs were derived by extrapolating in time using C.I. data, by extrapolating in wavelength according to -0.7 power of wavelength limit, and by extrapolating in diameter according to 2.7 power.

George Seielstad
December 7, 1988

Table 1
Capsule Summary

Discipline	Driving Science	Technical Requirements
Pulsars/Stars	Tests of General Relativity Surveys to greater galactic distances shorter periods Precision time grid	Diameter ≈ 150m class Frequency ≈0.05--3 GHz for pulsars --15 GHz for stars Frequency agile Sky coverage Declination < -30° (Gal. Center) Hour Angle: hours/day Time resolution: millisec to days Interference suppression Polarization important
Neutral Hydrogen	Largescale stucture of universe Structure of Milky Way Environments for galaxy formation Absorption against quasars	Diameter ≥ 100m Frequency ≈ 0.1--1.7 GHz Sky coverage Declination <-42° (Great Attractor) Hour Angle: hours/day Interference suppression Standing wave minimization Frequency resolution ≈ kHz Bandwidth ≈ 100 MHz Channels ≈ 1000s Multiple beams for Galactic HI surveys Blind surveys for galaxies Polarization purity for Zeeman effect
Spectroscopy	Extragalactic CO Heavy molecules in 20-50 GHz? ISM/Astrochemistry	Diameter ≈ 100m (50-70m at 115GHz) Frequency ≈ 0,5-115 GHz Frequency agile Simultaneous multi-transitions Rapid response to weather Sky coverage Declination <<-30° Hour angle: several hours/day Frequency resolution ≈ kHz to MHz Bandwidths ≥ 100s MHz Channels ≥ 10000s Standing wave minimization
Continuum	Sky mapping/source surveys VLBI, ground and space Cosmic Background Radiation	Diameter ≥ 100m Frequency ≈ 5 GHz for surveys ≥ 22 GHz for VLBI > 15 GHz for CBR Bandwidths maximized, >>100s MHz Sky coverage: horizon to horizon Multiple beams for surveys

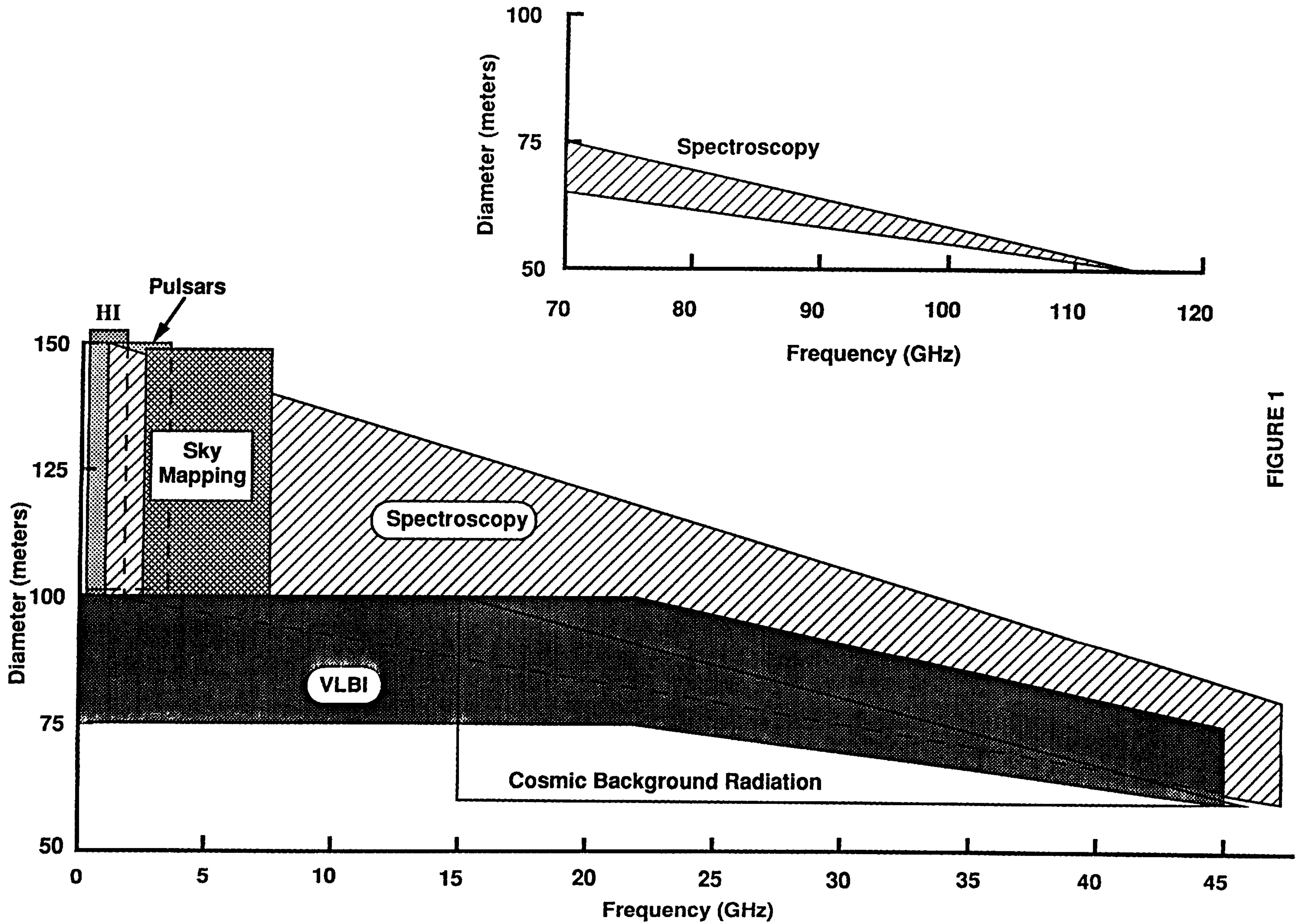
100
Diameter (meters)
75
Spectroscopy
50
70
80
90
100
110
120
Frequency (GHz)
Pulsars
HI
150
125
Sky Mapping
Spectroscopy
Diameter (meters)
100
VLBI
75
Cosmic Background Radiation
50
0
5
10
15
20
25
30
35
40
45
Frequency (GHz)

FIGURE 1

[Wed]nesday
[No]vember 30, 1988

the Charleston Gazette

Partly cloudy today with highs in the mid-40s. Variable cloudiness tonight with lows in the 20s. Details on Page 8A.

PARTLY CLOUDY

Telescope replacement speed urged

WASHINGTON (UPI) — Sens. Robert C. Byrd and Jay Rockefeller said Tuesday they want to see a proposal by January for the replacement of a destroyed radio telescope at Green Bank, W.Va.

The West Virginia senators met this week with officials of the National Science Foundation and the National Radio Astronomy Observatory to discuss the replacement of the 300-foot telescope, which collapsed two weeks ago.

"We told them we want to see a replacement telescope in West Virginia," Byrd and Rockefeller said in a joint statement.

"The message we delivered is that this type of telescope is important to scientific research, we think the telescope should be replaced as quickly as possible with state-of-the-art equipment, and we want to see it replaced in Green Bank," the senators said. "Now it's up to the experts to come back with their recommendation."

Officials told Byrd and Rockefeller the cause of the instrument's collapse has not yet been determined. The telescope was one of the largest of its type in the world.

"Green Bank is a unique research site — and an ideal location for a radio telescope — because it is a national radio quiet zone. We cannot afford to lose any time in moving forward with replacing this important scientific resource," Byrd said.

Observatory officials told Byrd and Rockefeller that plans for a replacement telescope would be drawn up following a meeting at Green Bank later this week. At the meeting, scientists from around the country are expected to discuss the needs of the scientific community.

"This is an enormously important facility. I believe that the scientific community worldwide wants to see a new telescope constructed at Green Bank. The basic data base of astronomy came from that dish, and now there is a void," said Rockefeller, who toured the site of the collapsed telescope last week.

Appendix B

Attendees at Green Bank Planning Meeting

Willem Baan	NAIC - Arecibo
Don Backer	UC Berkeley
John Broderick	VPI & SU
Bernie Burke	MIT
Brian Dennison	VPI & SU
Riccardo Giovanelli	NAIC - Arecibo
Martha Haynes	Cornell U
Carl Heiles	UC Berkeley
Bob Hughes	AUI
Ken Johnston	NRL
Jill Knapp	Princeton U
Frank Kerr	U Maryland
Jim Moran	SAO
Otto Richter	STScI
Dan Stinebring	Princeton U
Lew Snyder	U Illinois
C. R. Subrahmanya	Tata Inst.
Pat Thaddeus	Harvard-Smithsonian CFA

NRAO-VLA

K. Anantharamaiah
Robert Braun
Bob Hjellming

NRAO-Charlottesville

Alan Bridle
Bob Brown
Jim Condon
Dave Heeschen
Ken Kellermann
Harvey Liszt
Jay Lockman
Fred Schwab
Srikanth
Dick Thompson
Paul Vanden Bout
Al Wootten

NRAO-Green Bank

Wolfgang Batrla
George Behrens
Chuck Brockway
Mark Clark
Jim Coe
Allen Farris
Rick Fisher
Frank Ghigo
Len Howell
Rich Lacasse
Ron Maddalena
Roger Norrod
George Seielstad
Dwayne Schiebel
Jerry Turner
Ron Weimer
Dave Westpfahl
Steve White

Appendix C
Contributors to Planning Meeting

Marshall Cohen	Caltech
Frank Clark	U Kentucky
Steve Schneider	FCRAO
Jack Welch	UC Berkeley

NRAO-Tucson
Darrel Emerson
Phil Jewell

NRAO-Charlottesville
Joel Bregman
Dave Hogg

NRAO-VLA
Arnold Rots

From: CVAX::ABRIDLE 5-DEC-1988 12:39
To: @REPLACE,ABRIDLE
Subj: My reaction to Dec 2/3 meeting

Here are some observations and conclusions based on what I heard at the Dec 2/3 meeting at Green Bank.

A. Array vs Single Dish

The advantages of an array are:

1. Can provide large total aperture without the structural design innovation needed for equivalent monolithic antenna. This dominates choice if the required total aperture much exceeds equivalent of 100-m diameter.

2. Reduces pointing problems, wind loads for given final resolution.

3. Small elements might use conventional offset-feed geometries to minimize aperture blockage and get very clean primary beam.

4. Can place some control of beam shape in2hands of observer.

Tradeoffs are about even on:

1. Speed, and complexity of electronics, for large-area surveys (if the single dish uses array feeds for such work).

2. Initial construction cost (at about 100-m effective aperture); dish needs more structure, array needs electronics and computing. Much above 100-m aperture, array should win easily because dish requires pioneering design.

3. Self-calibration of atmosphere. Dish must have array feeds and a large correlator; array has what it needs anyway. Techniques are better developed for arrays, but principles are well understood for dish also.

4. Both can provide high surface brightness sensitivity and zero spacing data if all auto and cross correlations are used in the array.

The advantages of a single dish are:

1. Can keep electromagnetic path very clean by dismounting all unwanted receivers and feeds whenever it is important to have low sidelobes, little stray radiation and RFI, flat spectral baselines. Array elements get cluttered in practice because there is operational pressure to leave equipment for all wavelengths in place on all elements all the time.

2. Can make better use of state-of-the-art receivers, i.e. can run with prototypes and/or devote all maintenance resources to keeping a small number of packages in tip-top shape. Faster response to innovative . receiver design is possible.

3. Re-engineering of feeds and receivers is much cheaper because there are fewer of them.

4. Can be maintained and operated by less people, as there are fewer item to be maintained and attended to.

B. RFI performance

Green Bank's "trump card" as a site is the Quiet Zone, and much of the exciting low-frequency science (high-redshift HI, multifrequency pulsar work, etc.) requires exemplary RFI rejection capabilities. We should plan eventually to do whatever we can toward interference excision by signal processing. But we must get off to the best possible start by emphasizing RFI performance and primary beam cleanliness in the design of the antenna(s). The RFI environment will only get worse with time, so we must invest as much as possible now in design that will reduce far-out sidelobes.

The enormous generic advantage of interferometers for RFI rejection is based on fringe rate and delay discrimination. These advantages vanish asymptotically for compact arrays, though some use can still be made of them in practical finite arrays if the RFI is impulsive.

The worst RFI signals are from satellites, against which very clean beams are needed as the first line of defence. An array of small elements could use offset-feed technology to maximize clear aperture and so minimize I acceptance through far-out sidelobes. But an extremely compact array ght negate this for much low elevation work because of aperture blockage and scattering off adjacent dishes. RFI rejection would be best for a not-too-compact array of offset-feed dishes working near the zenith, or at azimuths and elevations for which blockage had been specially optimized (e.g. as one might do for the Galactic Center).

It will be difficult to use offset-feed technology for apertures of order 100m, except by illuminating off-axis sub-apertures from an on-axis minimum-blockage feed support (as was proposed for galactic HI work with the 300-ft before its demise). A new single dish should minimize use of massive feed supports, and perhaps maximize use of non-conducting guy wires with dielectric constants as close to unity as possible (are there any suitable strong materials ?) The single-tower geometry used on the Jodrell bank MkI, and the two-leg+guys geometry used on the 300-ft are preferable to a tripod or tetrapod, and modern versions of these should be considered.

A compact array would keep all the feeds closer to the ground than would a conventional dish with the same total aperture. This protects against local sources of interference getting directly to the feed, which may be an important problem at the lowest frequencies. The main RFI disadvantages of a compact array are dish-to-dish blockage, scattering and cross-talk. Most practical compact arrays (e.g. VLA D-array) have severe cross-talk problems, but none was aggressively designed to reduce this. We should be sure that we know how to eliminate self-interference before committing to a compact array.

C. Designs we should elimate now

The scientific goals presented at Green Bank ask for large apertures at ow frequencies, but significant residual aperture at 3mm. I think e should therefore eliminate the following options:

1. A single 70-m class antenna going to 3mm. This will be too small to do exciting science at the low frequencies for which the Quiet Zone is an ideal location.

2. A large-aperture array of many cheap dishes operating only to 5 GHz, e.g. off-the-shelf cm-wave communications antennas. This will be cheap to construct but relatively expensive to operate, and will not service the high frequency applications.

3. A single 100-m class antenna with a conventional off-axis feed geometry. The feed tower will be prohibitively tall if the path lengths from to the dish are equalized enough that the dish can be illuminated satisfactorily by a broad-band feed with a reasonably symmetric beam. We should however remain open (for a while) to suggestions for clever geometries that would reduce the tower height without exacerbating the illumination problem.

D. What's left ?

wo possibilities occur to me:

An inner-panel, outer-mesh dish giving 100-to-130-m aperture at low frequencies and about 70-m aperture to as high a frequency as we can afford. We should shoot for useful performance at 3mm, but back off to 1 cm if this cannot be done at reasonable cost. The dish should have an on-axis but minimum-blockage design; we should plan to support optional slightly off-axis feeds to illuminate a fully clear sub-aperture for work that requires the ultimate in sidelobe suppression.

2. An array with one (central) element that operates up to 3mm and a surrounding ring of about 6 equal-sized elements that operate only up to about 5 GHz. The outer elements might be off-the-shelf communications antennas, and would not be used for the highest frequencies. The ring might be made reconfigurable to meet the blockage and resolution requirements of different experiments. The element size should probably be about 40-m. Possibly we could use an offset feed clear-aperture design at this diameter.

I suspect that the array would be more scientifically flexible for a given construction cost, but that it would cost more to operate, and to keep equipped with state-of-the-art receivers, in the long run. If it was provided with a "generous" computer capacity at the outset, the computer might also contribute significantly to the VLA/VLBA computing problem, and thus give Green Bank an extra role as an array computing center.

marginally favor (1) because it would be cheaper to operate as a state of e art instrument, and so might be a better "matched filter" to the likely dget. But array options deserve a further hearing in-house, at least for a few more weeks.

Appendix D
Tim Cornwell

Along with everyone and his brother, I thought that I should send you some comments on the 300' replacement. I shall try to concentrate on arguments which have not been made before.

I have heard a report on the GB meeting last week, so I think I understand what the science is. It seems that with the possible exception of the nearby HI observations, all the science can be done with either a conventional big single dish or a very compact array. I do think that it is ridiculous to suggest building a very novel telescope of either type. This means that a 100m offset paraboloid is out! My feeling about the comparison between the two types of telescope is that, theoretically, both could do a good job. By this I mean that for the single-dish we would have to develop focal plane array technology substantially before it could compete with the array in imaging speed, data quality and the ability to correct certain errors like phasing and RFI. To take one example, selfcal for single dishes requires critically-sampled focal plane arrays, the like of which we will not be able to build reliably for at least a decade. Selfcal for arrays works now. Similarly, imaging (which is not a huge part of the science, but it is important) is slightly more awkward with focal plane arrays than with a compact synthesis array. No doubt we can improve this, but it will take time and effort. RFI rejection with a synthesis array will always be better, not because of fringe/delay descrimination, which also exists for a single dish (it corresponds to different focal points--that's all), but because first, the elements can be built with very low sidelobes if desired, and second, we know exactly what the synthesized beam is at any point on the sky (WSRT can remove Cygnus A 50 degrees away--try that with a single dish). This does, however, require some development. Overall, the technology behind a compact array is conservative; we could build one now:

25 x VLBA dishes	= $40M, say
Correlator from VLBA	= $ 5M (ballpark)
Computing	= $10-20M (do it right)

Some other odd points in favor of an array which have not been raised before are:

* It would give us an additional high frequency VLBA site even when the whole phased telescope is not used.
* It would be a good test bed for MMA techniques such as mosaicing.
* We would get good short spacings for the VLA straightaway.

Beyond that I have nothing more to say about the technical arguments for a compact array. Darrel's memo of last week summarizes these very well. I agree wholeheartedly that there is no scientific compromise in building a compact array and there are a great number of advantages.

Putting aside the technical arguments, it seems to me that there are a number of arguments for building a single dish. In decreasing order of importance:

* All our interferometer people are busy with the VLBA. We don't want to distract them now. Hiring more interferometer people is essentially impossible: all the good ones are taken by us or by other places like the AT.

* It is probably cheaper to operate. This may not be true if it were to be equipped with good focal plane array(s). Building something with high operating costs may well destroy the whole of NRAO since we would then not be able to do anything well, but rather we would be an exaggerrated version of the present situation of doing a number of things poorly.

* [Some comments here were edited out by Seielstad.] We should not destroy NRAO over a dispute between single dishers and interferometrists.

* We have not shown that an array can be easily used for spectral work. Now this could go both ways. The MMA must be an interferometric array and it must do spectral line well and simply. So we have to solve these problems. However, solving it now would be a big distraction from the VLA/VLBA.

[Unreadable line here] . . .
on technical grounds but the other arguments for the single dish are quite strong. If the 300' had not fallen down, and if we were not in this terrible situation of having to build this new telescope while the VLBA was being built, and if it did not have to go in Greenbank, then I would be totally opposed to a big single dish. In the current situation, I cannot say that the choice is so obvious, but, I prefer the single dish option.

I do suggest that if we do build the single dish, we should find some way of setting up a group at Greenbank to work on advanced single dish techniques such as the use of focal plane arrays. Rick Fisher once suggested something like this at one of our workshops on future instrumentation long ago. We are building up Socorro to be the center of excellence in interferometry, so why not sell the idea of Greenbank as a center of excellence in single dish observations. Obviously, if this project goes ahead, NRAO will be at Greenbank for at least 25 more years, so we should attempt to do it properly.

Tim Cornwell

December 6, 1988

To: Task Force for Green Bank Telescope
From: George Seielstad

Subject: **Tradeoffs and Compromises**

I) **Filling factor.** All scientific disciplines called for high sensitivity. Part of this was to be achieved via large collecting areas. Did all the area need to be in one aperture, or was a compact array wiser?
I opt for the single aperture for the following reasons:

A) Little or no capital cost savings were demonstrated for an array.

B) Annual operating costs of an array are higher than of a single, filled aperture throughout the lifetime of the instrument. The extra cost is the price paid for the added complexity.

C) Quality is compromised in an array. Individual receivers can be customized to perfection, the exact engineering opposite of a cloning process. Maintenance requirements also favor higher performance for one-of-a-kind than for an array. NRAO-GB, for example, can operate a maser on the 140 ft telescope, but only by assigning an engineer and a technician to it. Assigning a pair of skilled people to every element of an array is out of the question.

D) The argument that all filled-aperture telescopes will use focal plane arrays may be spurious. When focal plane arrays become standard, arrays will want them on each element.

E) Filled-aperture telescopes can approach the ideal of continuous frequency coverage much more readily than arrays. If changing frequency bands requires changing receivers, this can be done many times more quickly on a single dish than on an array. Upgrades, too, can be implemented more quickly.

F) Filled apertures can utilize wider bandwidths than can arrays.

G) Science decades into the future is unpredictable. A national center should therefore offer diverse instrumental options. NRAO is well stocked with arrays already.

II) **Frequency Range.**

A) Putting an upper limit to the telescope's performance at 5 GHz is too limiting.

1) Lifetimes of telescopes are reckoned in decades. No one can forecast science far into the next century. The wisest strategy is therefore to maximize options, and that includes offering the maximum feasible range of frequencies.

2) National centers have a responsibility to provide for the greatest number of users.

3) Every radio telescope ever built (with the exception of dipole arrays) has been pushed to perform at frequencies well above its design maximum. It seems foolish to expect this new telescope to be treated otherwise, particularly in view of the strong case made already for performance to at least 115 GHz.

2) HI could be observed for all $z<13$, getting into the regime of pregalactic pancakes.

3) Pulsar studies at ~100 MHz are diagnostic of the ISM.

III) **Offset Reflectors.** I favor a conventional design with strenuous efforts made to minimize blockage of the aperture, but recognize the advantages of an unblocked aperture are great enough to justify further investigation. I would recommend formation of a "tiger team" given until the end of March 1989 to investigate the prospects of nonstandard reflectors. My reasons follow:

A) Some significant fraction of interference, stray radiation (from parts of the sky outside the main beam), and standing waves can be attributed to radiation scattering or reflecting off feed supports. Eliminating these improves almost every observation.

B) At the same time, when observing near the maximum operating frequency of the telescope, almost half of the power is lost just to surface irregularities (when the telescope is considered in its transmitting mode). Therefore, unblocked apertures do not eliminate the entire problem.

C) Some data measured on an unblocked antenna in use showed improvements by 10-20 db over standard parabolas. The interference transmitted by a satellite (e.g., GLONASS), however, is so great that even attenuating it by 10-20 db leaves an overwhelmingly large unwanted contribution. Still, the suppression has greater effect if the satellite's signals are outside any radio astronomy observing band.

D) The few mechanical structures shown as examples of unblocked apertures were sobering to most, and frightening to some, once an extrapolation to dimensions of ~100m was envisioned. You still want to dangle something in front of the reflector without permitting any support structures to get in the way, an awesome challenge.

E) Major R&D would have to be put into feed design. The reflector is not illuminated uniformly or symmetrically. Possibly spillover will increase, because the illumination may have to be maximized at an edge of the reflecting surface.

F) Since the cosmic signals strike the aperture obliquely, the effective collecting area is reduced by the projection angle. Or, the same dollars buy less effective collecting area.

G) Because the reflecting surface lacks symmetry, more panel shapes will be necessary, adding to the cost.

H) Options worthy of study for a standard parabola reflector:

1) Single pole supported by several thin wires around periphery.

2) Knife-edge feed legs attached at dish's outer edge.

3) Different feed leg materials having a dielectric constant close to unity?

4) Do round feed legs scatter omnidirectionally more than rectangular ones? Do they reduce multiple reflections between primary mirror and other structures?

IV) **Recommended Telescope.**

PULSARS, RADIO STARS, SOLAR SYSTEM

D. Backer, J. Cordes, R. Hjellming, K. Johnston, D. Stinebring

We address three areas of science that would benefit by replacement of the 300-ft. telescope with a new large telescope: pulsars, radio stars and the solar system. These topics are joined by both commonality of astrophysics -- nonthermal processes in the vicinity of stellar masses -- and commonality of the signal characteristics -- rapid time variability, high polarizatio and correlated emission of high energy photons.

1. SCIENTIFIC JUSTIFICATION

Pulsars, novae, radio supernovae, and many of the interacting binary systems discussed below are united under the topic of the Death of Stars, which is emerging as a newly synthesized astronomical topic. In addition we deal with processes around normal stars, including our sun.

1.1. PULSARS

1.1.1. STELLAR EVOLUTION

Pulsars are rapidly rotating, highly magnetized neutron stars that are detected as a consequence of highly beamed, coherent radiation at meter and decimeter wavelengths. The neutron stars are formed in the final cataclysm of stars that once contained about ten solar masses. There are about 450 pulsars known. Their distribution in space is concentrated in the solar vicinity owing to the faintness of the pulsar signals. We estimate their distances by measurement of neutral hydrogen absorption, trigonometric parallax and column density of dispersing electrons. From this distribution we estimate that there are some 100,000 pulsars in the Milky Way galaxy. The study of the distribution of pulsars in the galaxy is essential to understanding the final stages of evolution of massive stars in the galaxy. This study will be enhanced by future efforts to first locate and then study a much larger sample of pulsars with the proposed Green Bank telescope.

Most pulsars are active for only a few million years. Then processes such as decay of their magnetic moment lead to a turn off of the coherent radio emission. This means that there is a much larger reservoir of neutron stars pervading the galactic disc. These radio-quiet neutron stars may be responsible for the gamma ray burst sources. Measurement of the trigonometric parallax and proper motions of a large number of the radio-active pulsars with VLBI techniques will complete our understanding of the present galactic distribution of the entire population of neutron stars.

Several pulsars are directly related to historical supernovae. Their study and the detection of more distant and perhaps somewhat older pulsar-supernova correlations provides a critical link between the stellar explosion and implosion event that marks the death of massive stars.

There are now eight pulsars with millisecond periods and 12? binary pulsars whose evolutionary histories are distinct from the ordinary pulsars discussed above. We do not know for sure, but some number between a few and ten percent of the pulsars that are discovered are in this remarkable category. Each new system that we find leads to new insights about the evolutionary paths of massive stars. The first binaries clearly showed that not all binaries with either high mass or low mass companions are disrupted. There was evidence for spinup of the neutron star following its formation and subsequent spindown. This was the best explanation for the 1.5 millisecond pulsar detected in 1982. The 1987 detection of a millisecond pulsar that is ablating its 0.02 solar mass companion completes this picture. Many of the evolutionary ideas for these objects have come from astrophysicists investigating low-mass X-ray binaries.

Globular clusters are factories for production of low-mass binaries, and theoretical notions led us directly to the detection of millisecond pulsars in globular clusters. These dense star systems are concentrated around the galactic center. More sensitive searches for globular cluster pulsars will be done if a large telescope is available and new objects will necessarily be found and will clearly be important additions to the pulsar zoo. The pulsar detected in M15 is now showing a period spinup which must result from acceleration in the potential well of the cluster that is an order of magnitude higher than previously expected.

1.1.2. FUNDAMENTAL PHYSICS

Millisecond Pulsars and a Gravitational Wave Background

Millisecond pulsars have been proven to be as exciting as they were unexpected upon their discovery in 1982. They have opened up new lines of research in cosmology and fundamental timekeeping as well as pushing established areas of pulsar research to unheard of levels of accuracy. none of the eight known millisecond pulsars has ever exhibited timing irregularities when measured against the best atomic clocks. This fact sets an already stringent limit on the presence of gravitational radiation left over from the earliest stages of the cosmic expansion, since broad classes of models predict the presence of long wavelength (light-years) gravitational radiation that should cause irregularities in high accuracy pulsar timing. The upper limit on energy density of $<4 \times 10^{-7}$ the energy density needed to close the universe scales very favorably with improved timing accuracy and duration of the timing effort. This limit scales with the timing accuracy δt and the data span T as $(\delta\tau)^2/T^4$, making this an outstanding long-term project with many spin-off projects. Furthermore, the sensitivity to a gravitational wave background increases when a number of stable pulsars, widely spaced in ecliptic longitude, are compared, making this an ideal project for a large-aperture, fully-steerable dish such as the VLD. At present, US radio astronomers lead the world in the high accuracy timing of millisecond pulsars. They have found four of the eight known ones, including the first and fastest one and the recently discovered millisecond pulsar in an eclipsing binary system. Most of this work is now done at Arecibo, but the sky coverage limitation — particularly toward the Galactic center — has hampered searching and follow-up timing observations of these important objects.

The VLD would immediately become a forefront instrument in the search for and timing of millisecond pulsars. The key parameters for this effort are:

1. a large collecting area ($(150\text{ m})^2$ equivalent),
2. a good interference environment at frequencies from 400 — 800 MHz (Arecibo is particularly bad in this respect, being situated near a number of major naval bases), and
3. a compact collecting area (an array design would reduce searching sensitivity by reducting the solid angle searched in a given observing time).

Very sensitive searches for millisecond pulsars could be conducted with the VLD, taking full advantage of its large collecting area, the good RFI environment in Green Bank, and the full sky coverage. As more millisecond pulsars are found, both with the VLD and with other instruments, the millisecond pulsar timing program could be expanded to include all but the most southerly of these. Since a high percentage of millisecond pulsars are in binary orbits and have other interesting properties in common, a long-term timing program can be expected to produce a continuing stream of results. Areas besides the search for a Gravitational Wave Background which would be well suited to VLD research include ISM studies, long-term stable timekeeping (of great interest to the national timekeeping services), high-accuracy astrometric comparisons, measurements of their distances and space velocities, and the exploration of the environment near close binary systems. Much innovative millisecond pulsar work has been done in the US. The teaming up of a large, fully steerable dish such as the VLD and the extremely high sensitivity of Arecibo make an outstanding combination, and one that will put the US capability in this field far ahead of its competitors.

Binary Pulsars and General Relatively

Binary pulsars continue to be our best laboratory for probing the high-velocity, dynamic predictions of General Relativity, including the production of gravitational radiation and the consequent spiral-in of these systems. The original binary pulsar, PSR 1913+16, continues to yield new results on a yearly basis. The latest comparison between the high accuracy timing observations, conducted at Arecibo, and the gravitational radiation prediction of General Relativity are in agreement at the 2% level. This fundamental measurement is still the only evidence for the existence of gravitational radiation. There are now 12(?) binary pulsars (six of them also millisecond pulsars) out of 454 known pulsars. Two of these were discovered in searches at the 300-ft. and many more could be found at Green Bank using the VLD. While not all binary pulsars can be used to test General Relativity or alternative theories of gravity, systems with periods that are reasonably short and have measurable eccentricity will increase our ability to probe fundamental physics. Although it is obvious that limited sky coverage and tracking range hamper efforts to find and time binary pulsars, it may not be generally appreciated that an enormous collecting area, such as that at Arecibo, is not essential for timing most of them once they have been discovered. In the search phase, a good RFI environment is even easier because of the large signal-averaging advantage of a typical timing observation relative to search observations.

The original binary pulsar is still the best probe of General Relativity that we have. The startling report of a millisecond binary pulsar in a 33 minute, elliptical orbit by observers at Parkes (64 m) has still not been fully confirmed, but it is clear that they have discovered two millisecond binary pulsars in **a single beam area** (containing the rich globular cluster 47 Tucanae). This system, which they claim has a relativity-induced periastron advance of 0.6° /day (PSR 1913+16, by comparison, advances at 2.3° /year), may turn out to have been a false alarm. But it reminds us that pulsars continue to surprise even the most experienced observers with their variety and application to basic new problems in astronomy and physics. We have certainly not found the most unusual or informative binary pulsar system. Searches with the VLD may turn up a system as spectacular as two pulsars (one of them a millisecond pulsar) in a close — and rapidly decaying — binary orbit. This double-line spectroscopic binary would provide a field day for General Relativists and astronomers alike. Or, perhaps, the VLD will find more examples of pulsars in extremely tight, eclipsing orbits such as the recently discovered PSR 1957+20. Such discoveries would continue to shed light on the progenitors of millisecond and binary pulsars, and would improve our understanding of the late stages of stellar evolution.

Again the main requirements of the VLD for this work are an excellent interference environment (including active interference excision), large collecting area, and full sky coverage. This instrument would be one of the fastest pulsar searching machines in the world, exceeded only by Arecibo and then only over its limited declination range — which of course does not include the important Galactic center region. The capability of the VLD for binary pulsar searching will be enhanced by real-time signal processing capability and dynamic interference rejection. Some thought should be given to making an IF port available always for piggyback pulsar searching (or SETI work), although in our era of still fairly limited computing power most of the VLD searching effort will take place in carefully planned programs. Looking ten or fifteen years down the line, however, computing power may increase to the point that routine pulsar searching through data obtained in piggyback mode will be commonplace. The VLD signal processing path should be designed with this possibility in mind.

Another probe of General Relativity comes from the search for geodetic precession of pulsar spin axes. Detection of this effect would imply discovery of a new general relativistic effect with the subsequent ability to sample the pulsar beam in two dimensions.

The search for and subsequent timing of binary pulsars has been an area that US radio astronomers have led the field in. We can continue to improve upon this record by moving aggressively forward to an instrument with world-class collecting area, extensive signal-processing capabilities, and full-sky coverage in a radio-protected zone.

1.1.3. Neutron Star Interiors and Magnetospheres

Neutron star structure and the underlying equation of state are accessible through the discovery of millisecond pulsars with near breakup periods, through the observation of forced or free precession of the spin axis (pulse shape and polarization temporal variations), and through rotation fluctuations (glitches and random walk timing noise). Millisecond pulsar discoveries require maximal collecting area combined with large data rate dynamic spectra acquisition and substantial post-processing power. Pulse shape and timing studies require monitoring over a variety of time scales.

A host of phenomena include rapid intensity and polarization variations on time scales of microseconds on up. Evolution of pulse shapes with radio frequency suggests variable altitude emission, but these issues of geometry, magnetic field structure, and relativistic beaming are poorly understood. Frequency coverage from 50 MHz to a few GHz is necessary for further progress. To thoroughly optimize pulse timing to achieve the full potential of pulsars as clocks requires better understanding of how pulse features are locked to rotational phase. Multiple frequency timing observations are needed to separate interstellar propagation perturbations from magnetospheric terms (aberration, retardation, and gravitational ray bending effects).

The relationship of isolated radio pulsars to progenitor systems such as low mass X-ray binaries and QPO systems is not yet understood in an evolutionary scheme. Searches for intermittent pulses may yield clues to this relationship. Such objects may appear for short intervals as radio pulsars (low density magnetospheres) that are quenched by intermittent accretion from a companion that overflows its Roche lobe intermittently (instabilities, illumination from the pulsar imply an induced wind). Cross disciplinary work between radio instruments and high energy observatories (ROSAT, AXAF, GRO) is likely to yield exciting discoveries.

1.1.4. Pulsar Radio Emission

There are many exciting studies of the pulsar emission mechanism that have not been attempted in recent years because of the limited tracking range of the 300-ft. and the limited frequency coverage of the Arecibo telescope. One such project is the study of how the highly polarized emission from single pulses evolves with frequency. The dispersed nature of pulsar pulses allows us to observe an individual pulse over a range of widely spaced frequencies. This would be an excellent project for the VLD because of its large collecting area and good frequency coverage. Another area of studies that could be undertaken with the VLD is the study of pulsar nulling and subpulse drifting ovewr long stretches of time (many hours to a few days). We do not know what happens to subpulse drifting over long stretches of time (many hours to a few days). We do not know what happens to subpulse drifting during pulsar nulls for a reasonable sample of pulsars. We could study this for a number of interesting pulsars that are circumpolar at Green Bank with the VLD. Low-frequency polarimetry (50—300 MHz) and multi-frequency waveform studies of many pulsars that are not visible from Arecibo are other good projects for the VLD. It may also be advantageous to use the VLD for dual-frequency observations of pulsar single pulses, observing at low-frequency with the VLD and using Arecibo's additional collecting area for observations of the same pulses at higher frequency. The combination of the large collecting area of the VLD, its wide and nearly continuous frequency coverage, and its full sky coverage will make it a very valuable instrument for studies of the emission physics of radio pulsars. The inclusion of a powerful spectral processor with this instrument (such as the one almost completed at Green Bank) will be essential to the full study of these emission physics problems.

1.1.5. Interstellar Medium Studies

Pulsars provide a unique means for probing electron density microturbulence on sub-AU scales via diffractive and refractive scintillations and via pulse timing variations. Dynamic spectral observations yield the column density of scattering material which shows enormous (factor of 10^5) variations between lines of sight. The turbulence is most likely related to regions of cosmic ray acceleration. It appears likely that multidisciplinary radio, x-ray and gamma-ray studies will be very fruitful. Further progress in the radio needs observations of as many pulsars as possible, particularly towards the galactic center.

1.1.6. Support for Space Missions

One of the major pulsar projects planned for the 300-ft. at the time of its collapse was a timing program in support of the Gamma Ray Observatory, planned for launch in 1990. GRO will be searching for pulsed gamma rays from about 300 radio pulsars. In order to fold the gamma ray photons at the correct pulsar period and phase it is essential to make pulsar timing observations on the radio source list contemporaneous with the gamma ray observations. The 300-ft. was to be the primary instrument for timing about 100 of these pulsars; the remainder will be timed at Jodrell Bank and Parkes. The VLD could do this job faster and for an extended source list because of its increased sky coverage.

This is only an example of the sort of support for space astronomy that could be provided by the VLD. Another type of space mission that may call for simultaneous observations of pulsars with the VLD are x-ray telescopes observing accreting binary sources, including QPO's. The VLD would be the primary instrument for support of this sort of mission in the US, because of Arecibo's limited declination range. Although we do not expect that a large fraction of pulsar observing time on the VLD would be spent in support of space missions, the need does exist and the scientific gains from these multi-spectral studies of neutron stars will far exceed the proportion of telescope time devoted to them.

1.1.7. Other pulsar projects

rotation measures

dispersion measures, scattering, and profiles toward the Galactic center

HI absorption studies toward pulsars

Astrometry - ????

1.2. Stellar Radio Sources

A large variety of stellar radio emission phenomena have been found in the last two decades. However, most, with the right sensitivity and time/frequency sampling not yet available, and being intrinsically weak, have only been partially studied in a small number with the strongest, most favorable characteristics. This is also a field where, unlike much of radio astronomy, the scientific problems are intrinsically multi-wavelength. Thus in most cases the study of radio-emitting regions of stellar environment is only a part of the information/data available. This is an ideal situation for scientific progress when there is clear coupling between different observational diagnostics, but poses special need for supporting and coordinated programs under many circumstances.

The majority of known radio star phenomena are mainly 2-90 cm "events" with time scales from ms for the most compact, highly energetic phenomena to seconds, minutes, hours, and days as the size and velocity scales change. The objects with the shortest of these time scales are either compact systems like black hole binaries, neutron star binaries and white dwarfs, or they are intense, high surface brightness phenomena as found in flare stars and certain active binaries.

Flare stars, of which some tens are radio sources, and a few like UV Ceti and AD Leo have shown the strongest tip-of-the-observable-iceberg of ms-seconds, coherent, highly polarized radio emission regions on stellar surfaces. Stellar surface activity in binaries is the most spectacular and is commonly found because synchronous co-rotation forces magnetic dynamo action to levels considerably above what isolated stars can achieve. In many cases radio activity observations directly see field-plasma interactions on scales 10**4-10**6 times the largest equivalents ever seen on the sun. However, distance weakens the signals to levels requiring the largest possible collecting areas to sample the minutes-hours time/frequency characteristics of changes or events.

Many active systems like RS CVn binaries and Algol systems probably exhibit intra-stellar magnetospheric phenomena. These are analogous to taking Jupiter magnetospheric phenomena, scaling them up to stellar sizes, and forcing interactions between two such systems with field-particle exchange, included plasma instabilities, and related relativistic phenomena.

Compact-object physics exhibits the most exotic and extreme forms of stellar radio emission. X-ray binaries like Cyg X-2, SS433, and Sco X-1, at distances of hundreds to many thousands of parsecs, produce spectacular radio emission briefly joining the company of the strongest compact sources in the radio sky. Jets and dynamical outflows couple to 10**12 cm and more radio jets/ejecta with very high velocities (1/4-1/3 c), with coupling time scales from tens of minutes on up. The radio phenomena are directly effected, and in effect different diagnostics of observed changes in the structure of X-ray emitting accretion environments. SS433 and Cyg X-3 are cases most cases, and most events in even these objects, are so compact one has only radio spectrum and time evolution diagnostics, requiring sensitivity, frequency agility, and rapid sampling on time scales of minutes to hours to days. A large collecting area, cm-instrumented, when occasionally used with the VLBA, could provide fundamentally important imaging of these jets or outflows.

Nova shells, recurrent novae, and radio supernovae are all phenomena where radio observations determine some of the parameters or effects of explosive phenomena on stellar "surfaces", mainly studying ejection of material previously and sometimes simultaneously seen at optical, UV, IR, and occasionally X-ray wavelengths. Novae shells are mainly pure ejecta, where lower energy ejecta interact with external matter in the form of a pre-existing wind. Much stronger are the radio supernovae, where massive explosive energy produces prodigious radio-emitting relativistic plasma seen as evolving radio events. X-ray binaries (GS2000+25, A0620-00, Cen X04), at intervals of tens of years (or more), have such drastic and brief changes in accretion environments that dynamical events produce prodigious, evolving volumes of radio-emitting relativistic plasma.

Symbiotic stars, VV Cep binaries, and planetary nebulae are cases where interacting winds and dynamical ejection phenomena produce moving structures whose evolution is seen in the form of their thermal radio emission, providing information about energies, masses, and velocities.

Hot wind outflows are not only directly radio observable diagnostics of mass loss rates and size scales, but fortunately or unfortunately have external interactions or instabilities that generate transient non-thermal, radio-emitting plasmas. This is possibly the most benign form where stellar outflows generate high energy, non-thermal radio phenomena.

Cools winds (Betelguese, Antares, ...) exhibit radio emission from their chromospheric levels, giving diagnostics of density structure and mass loss rates. This occurs in the 1-5 stellar radii regions where the winds are energized and accelerated. In some binaries (VV Ceph type) companion hot stars light up radio-emitting HII sub-regions in the cool winds. In some cases, changes are seen because of change of observational aspect with change in binary motion. Si0, H20, and OH masers are spectroscopic probes of other layers of these cool winds. They also play a special role in galactic dynamics studies.

1.3. Solar System

1.3.1. Sun

Now, the Sun. A large, fully steerable single dish would not only be quite nice as a supplement to high resolution imaging with the VLA (i.e., fill in the hole in the uv plane at several frequencies), it would be extremely useful as a solar imaging instrument in its own right at wavelengths shorter than 10 cm. The microwave spectrum of the non-flaring Sun has never been adequately characterized. For example, there remain difficulties in the interpretation of optically thin EUV line emission from the solar transition region and microwave emission — the two imply rather different physical conditions in coronal holes and in quiet regions. The ability to image the Sun at several frequencies (high resolution is not necessarily a priority in this instance) would be extremely useful in approaching this problem. Further, solar cycle variation of the microwave emitting properties of the Sun have never been clearly defined over a wide range of frequencies. A program of routine, low-resolution solar imaging would be useful in defining solar cycle related changes in the upper chromosphere and transition region in coronal holes, quiet and active regions.

Finally, solar flares. Here, both a dynamic spectral capability and a frequency agile capability would be extremely valuable. (By the way, by "dynamic spectroscopy," I mean sampling a relatively narrow bandwidth with high temporal and spectral resolution with a correlator; "frequency agility" implies much coarser spectral resolution over a much broader frequency range arranged by multiplexing over a bank of receivers, or maybe the broadband signal could be chopped up and pushed through in parallel.) While pretty good spectral information has been available in the past for solar flares, it was usually obtained with small dishes or simple interferometers. As a consequence, it was not always possible to determine where the flare occurred on the Sun. Joint experiments involving both the imaging capability of the VLA and the frequency agile capability of OVRO have proved to be very useful, but OVRO has no dynamic spectral capability and has no capability at all below 1 GHz. So, a large new single dish could be useful in at least determining which active region a particular flare occurs and might also provide a low-frequency dynamic spectral capability.

1.3.2. PLANETS JUPITER? POLN ???????

2. TECHNICAL CONSIDERATIONS

2.1. TELESCOPE

We favor the unique capability of a 150m diameter equivalent aperture (60% efficiency) with declination coverage from -45 deg declination, to the pole. While a single-dish is easiest to think about, it seems that the collecting area (G/T) will be maximized by a small number of phased apertures. In fact, the faint continuum radio star work requires some form of interferometry to reduce confusion and perform sky subtraction. This is offset by the complexity of electronics that in the single-dish is bypassed by the free space formation of a beam. Searching for new pulsars would require in either case the formation of many independent beams in order to cover a given solid angle in a reasonable amount of time.

RFI is a major concern at meter and decimeter wavelengths for this science. While the NRQZ at Green Bank is valued, sidelobe minimization is a key design criterion. Dynamic RFI excision is assumed to complement a low sidelobe level design.

2.2. RECEIVER/FEED

The principal science discussed would be conducted between 50 MHz and 3-5 GHz for pulsars and up to 10-15 GHz for radio stars. Polarization properties are important since all signals are highly polarized in both circular and linear. The high polarizations may assist in calibration, although the signals are also highly time variable.
Access to all radio frequencies is desireable with rapid switching between bands and octave feeds below GHz.

2.3 BACKEND

This research requires extensive real-time processing above and beyond the needs of most radio astronomy. This is for many reasons; among them are RFI excision, dispersion and Faraday rotation removal and measurement, interstellar scattering effects, and adaptive observing based on signal strengths. A powerful and flexible signal processor is essential to make use of a new capability. This would be attached to the IF signal of a single-dish telescope, or to the phased array output of a multi-aperture system. The temporal behavior of the latter would need to be "clean" on time scales from milliseconds to minutes. For pulsar searches the capacity to deal with the many beams formed is required, and the number of beams would likely be larger for an array than for a single-dish.

3. RELATIONSHIP OF VLD AT GREEN BANK TO US ASTRONOMY

The new telescope will enhance and complement the US capability for pulsar and radio stars well beyond the present and planned capability of the Arecibo and VLA telescopes.

Draft ϕ

RESEARCH IN THE 21 CM HI LINE

C. Heiles, J. Lockman, R. Fisher, R. Giovanelli, M. Haynes, O. Richter

EXTRAGALACTIC HI

The field of extragalactic HI studies has expanded in a variety of extremely fertile areas over the last ten years. Some of these are outgrowths of classic problems in astronomy, but most represent bold incursions outside traditional territories of research. The elasticity of operation and high sensitivity of radio telescopes with large collecting areas is the key to approaches to such diverse areas as:

(a) the large-scale structure of the Universe, its scale parameters, and the local and large-scale deviations from smooth universal expansion;

(b) the mass and light content of low-luminosity density regions of the Universe, via the study of low-surface brightness, optically faint galaxies;

(c) the structure of galaxies soon after their formation, through the study of HI absorption lines against the continuum of quasars and other distant background sources;

(d) the study of structure and evolution of galaxies and clusters of galaxies, the issue of genetic versus environmental effects, as revealed by the measurements of neutral gas content;

(e) the structure and dynamics of small groups of galaxies, using the gas as a tracer of tidal interactions, mergers, and infall phenomena.

These investigations typically require the observation of large statistical samples, in survey mode, over the whole sky. They are best suited to telescopes with very large apertures, great operational flexibility, and in an interference-free environment.

In recent years, the 21-cm HI line has proved an invaluable tool for mapping the structure of the galaxy distribution in the local Universe. Whereas the redshifts of high surface brightness, early type galaxies in clusters are best suited for optical studies, the HI observations of gas-rich spirals and irregulars allow astronomers to trace the more widely dispersed populations on supercluster peripheries. Because of recent advances in receiver and spectrometer technology and feed design, the number of redshifts contributed by 21-cm techniques has risen eight fold in the last 15 years. Recent studies of the large scale structure made with the 300 foot have concentrated on the local Universe at $v < 10{,}000$ km/s^{-1} and were restricted primarily by the limited tracking and sky coverage and by the spectrometer (whose replacement was imminent).

Current studies of large scale structure volumes ($v < 10,000$ km/s) have revealed the existence of structures at least as large as the volume sampled. In order to determine the sizes of the largest structures, it is necessary to continue to map the Universe over a deeper volume. For a 150-m telescope a moderate luminosity spiral with $v \approx 15,000$ km/s^{-1} could be detected in less than one hour (assuming $T_{sys} \sim 20$ K). There are at least 20,000 such objects in the sky visible to Green Bank (and not Arecibo). A large aperture with more tracking capability and declination coverage will provide enormous possibilities for mapping large-scale structure in over 70 percent of the sky (two-thirds of which is not visible from Arecibo) including the critical Hydra-Centaurus region.

In addition to allowing the measurement of redshift distances, the 21-cm emission spectrum, when combined with data taken at optical or infrared wavelengths, provides a second, redshift independent means of estimating distances. Since its recognition by Fisher and Tully twelve years ago, this technique has been studied and refined so that it now promises to provide distances of highest possible accuracy. In the future this method will be used to study a variety of questions in the local velocity field, the scale of the Universe, and the possible expansion of large-scale voids. By necessity, this technique requires the collection of large samples of high-quality 21-cm spectra.

It should be pointed out that future studies pursued in this area of research at Arecibo and Green Bank will be highly complementary. Because of its larger collecting area, Arecibo, with its future Gregorian optical system, will always be able to achieve greater sensitivity to more distant objects, but only in a limited range of declination. At the same time, a fully steerable 150-m telescope in Green Bank would provide the greater sky coverage. As today, astronomers will take advantage of each telescope's unique capabilities.

BLIND SEARCHING

In the 20-25 percent of the sky occupied by the Milky Way, it is difficult or impossible to see external galaxies because of the obscuration by dust in our Galaxy and the confusion produced by the high density of stars. Recent pilot studies have shown that it is possible to find galaxies in this region by blind searching at 21 cm. Similar observations have been carried out away from the Milky Way to act as a control, by comparing a sample of galaxies selected at 21 cm with the sample selected optically.

These studies require large collecting area and could be well continued with the proposed telescope, using a multi-feed system in the interests of search speed. Away from the immediate vicinity of the galactic equator, the search for spirals can be assisted by picking out objects from the IRAS survey which have galaxy-like spectra. A 21-cm census of all the spiral-irregular, and gas-rich galaxies in the zone of avoidance behind the Milky Way would be very valuable for extending the declination range over which we can study the overall large-scale structure.

LOW OPTICAL LUMINOSITY OBJECTS

Recent work has shown the existence of a number of gas-rich, low-mass extragalactic objects which are difficult to detect optically. The new telescope, in conjunction with the Hubble Space Telescope and other space observations, should enable many more of these objects to be studied at 21-cm and their relationship to other types of galaxies understood. These gas-rich objects are of great interest in relation to theories of galaxy formation, and it is especially important to see how their density varies across the sky, and whether they are found inside voids where larger and more massive galaxies are almost absent.

A large collecting area, tracking ability, and freedom from interference are important for these studies.

HIGH REDSHIFT HI ABSORPTION STUDIES

The discovery of metal-rich absorption-line systems in spectra of high redshift quasars has triggered new interest in the absorption line studies. The absorption arises in extended disks of objects comparable to today's spiral galaxies. This field of HI research will become more and more important as new (or improved) facilities like HST, ROSAT, AXAF, etc., come into operation. Detection of HI absorption may occur at substantially lower column densities than HI emission. Thus, probing lines of sight through galactic (or pre-galactic) disks at varying radii will provide strong constraints for theories of galaxy formation. It will also lead to better understanding of the universal UV radiation field in the early Universe, and, hence, of the UV and X-ray background radiation.

Currently infeasible, a measurement of the time dependence of z in high redshift HI absorbers would perhaps lead to direct measurements of structure and turbulence in very young objects. Using large samples spanning the redshift range $1 \leq z \leq 3$, we might have hope to observationally determine the structure of the Universe (q0).

HI CONTENT

With improvements in receiver technology, the study of global properties of galaxies (such as total mass, HI mass, mass-to-light ratios, surface densities, etc.) has moved to progressively less HI-rich objects in recent years. Very early type galaxies had conventionally been thought of as extremely gas poor. Recent advances in other wavelength domains (X-ray, optical, IR) have shown this to be untrue. With the 300-ft telescope we were beginning to detect those elliptical and S0 galaxies with the largest amounts of neutral gas (a few times 10^8 Msun). A large filled-aperture radio telescope is optimally suited to study the low gas column density peripheries of spiral disks. These regions are dynamically fragile, easily perturbed by neighboring objects and the intergalactic radiation field. The 21-cm line provides the dominant and most easily detectable emission from these regions, and the only means to fully probe their dynamics. With much higher sensitivity (larger dish, tracking), we can hope to detect well over 50 percent of all early-type galaxies. This would lead to advances in understanding of the importance of disks in early-type galaxies. The distribution and origin of the gas in early-type galaxies (infall vs. external merge) and early type galaxy formation and evolution in general. With improved frequency agility and interference suppression we will be able to study the change in relative HI content in very gas-rich systems such as Sc galaxies as a function of redshift.

Because most clusters of galaxies are not yet in dynamical equilibrium at the current epoch, we expect to see strong evolution already at relatively low redshift ($z < \sim 0.3$). Studies of the HI "deficiency" of galaxy populations in clusters as a function of z will provide new insights into the origin of the hot (and metal-enriched) intergalactic gas visible in X-rays.

<u>A very important technical point for extragalactic HI:</u> We need many spectral channels. For redshift searches of galaxies, V = 0 to 15,000 km/s is the relevant range. This is a total bandwidth of order 50 MHz, and one requires a resolution of 2 km/s, which means about 8192 channels (PER RECEIVER, PER FEED--2 polarizations x 7 feeds means 14, 8192-channel correlator). This is a significant requirement, both for initial construction costs and for data reduction (because the observer wants ON-LINE, REAL-TIME data display to decide when to stop integrating!).

BUT MORE IMPORTANT is searching for high z HI. One wants to spread these 1.2×10^5 channels over bandwidths of 400 MHz -- so, 1000-1400 MHz, 600-1000 MHz, 200-800 MHz might be reasonable (but better: over ~300 -> 1200 MHz simultaneously).

These capabilities might be expensive, but they are important, and we should realize that we need them at the beginning.

TECHNICAL REQUIREMENTS

The most important property of an instrument designed for extragalactic HI observations is high sensitivity. This means a maximum ratio of effective collecting area to system temperature. A minimum set of values for a fully steerable antenna is 100 meters aperture with an efficiency greater than 55 percent and a system temperature of 10 K. An aperture of 150 m is very desirable.

Interference below 1400 MHz is a severe problem and will get worse. Far sidelobes must be suppressed by at least 10 dB and preferably 20 dB below those of the current generation of antennas. Even with this added protection, spectrometers must be designed to handle interfering signals many orders of magnitude stronger than the minimum detectable signal strengths.

Maximum sensitivity must be maintained over the 700 to 1420 MHz range with relatively little loss down to about 200 MHz recognizing that the sky background temperature will become a dominant factor below 400 MHz. Short-term frequency agility is desirable, but should not override the desire for maximum sensitivity.

The sky coverage must be +90 to -45 degrees declination with the southern limit being subject to cost trade-offs. A southern limit higher than -40 degrees is not acceptable. Tracking time must be at least several hours around the meridian. Survey for optically invisible objects will require at least seven, and preferably many more, simultaneous beams of high efficiency.

Sidelobes within 20 degrees of the main beam should be 20 dB below the main beam. The ellipticity of the main beam should be less than 0.3 at all declinations and not change substantially while tracking. Pointing accuracy must be better that a tenth of a half-power beamwidth maximum deviation. Polarization purity is a minor consideration. A slew speed greater than 20 degrees per min. and an acceleration rate greater than 5 degrees/min/min are acceptable in both altitudes and elevation. Higher values are desirable.

NEAR GALAXY

Near extragalactic and halo gas covers three regimes of space.

1. Magellanic Stream gas (50 kpc distant)

2. High velocity gas ($|v|>100$ km/s) which may include a variety of phenomena whose distances range from kiloparsecs to tens of kiloparsecs.

3. Halo gas at intermediate velocities ($50 < |v| < 100$ km/s), distances of order of kiloparsecs.

None of these regimes have been well studied with resolutions of less than 30'. In view of their distance, small angular scale structure is expected, and, in the limited cases that have been studied, is seen. Synthesis observations of three high-velocity clouds show that typical structures are 3' wide.

It is clear that what happens at the Galaxy's edge or at the edge of HI clouds in nearby intergalactic space is very interesting because there the gas is exposed to the intergalactic ultraviolet flux. High sensitivity, high resolution, and high dynamic range observations are required for mapping clouds in all three regimes so as to reveal both the structure within them and the physical nature of their boundaries.

1. Magellanic Stream gas. Clearly an intergalactic phenomenon, a few sections of the Stream have been mapped with the Arecibo beam. Area mapping will provide indisputable information regarding the interaction of the intergalactic UV flux with neutral gas. The nature of condensations within the Stream (velocity width, volume density, and morphology) will allow the dynamics of the Stream to be accurately modelled.

2. High velocity gas. The published parameters for the northern hemisphere high-velocity clouds shows a strong dependence on angular resolution. Due to the existing lack of a suitable fully steerable telescope, virtually no high-resolution data on any of the clouds exists (the major ones lie well outside the Arecibo telescope range). All sky-surveys of the high-velocity gas will reveal systematic differences in the galactic-scale morphology and observed parameters between clouds that may be members of different populations of objects; e.g., distant spiral arms, expanding supershells, local infalling gas. Such data would, in turn, be used as a finding list for even a more detailed study with the VLA.

3. Halo gas. No good inventory of halo gas exists. Copernicus and IUE observations have provided evidence that superbubbles in the galactic plane create outflowing winds of hot gas which is expected to cool and fall back to the plane. Very faint emission (0.01 K, 10 km/s broad) has been found in some regions of sky in the intermediate velocity regime. It requires high sensitivity, high resolution, high dynamic range observations with good baselines to reveal the presence of condensations of neutral material in this return flow. As is the case for the other two regimes, the existence of shock boundaries between the clouds and either halo or intergalactic space can only be recognized through making these types of observations.

TELESCOPE

Each of these regimes requires high resolution, high sensitivity, and high dynamic range observations with low sidelobe structure to avoid contamination from galactic hydrogen. Available data suggest that a beam of between 3 and 9′ is necessary to allow both the capability to map large areas (with a multi-feed system) and study details on a scale known to exist.

LARGE-SCALE GALACTIC STRUCTURE

Study of the large-scale structure of the Milky Way disk provides a picture of the time history and current evolution of spiral galaxies, and of the processes which sculpt and shape galaxies from more primitive material. The large-scale structure of the Milky Way disk is a matter of continuing concern, three decades after the discovery of interstellar hydrogen. Specific areas of uncertainty include: the distribution of gas in the nuclear (central 1 kpc) region and the relationship between the gas reservoir and energetic phenomena observed there; the distribution of neutral material across the disk and its partition between spiral arm and interarm regions; the rotation curve of the Milky Way, from which the overall distribution of matter (stellar, gaseous, and dark) is inferred; departures of the disk from co-planarity at larger galactocentric radii (warping); flaring or broadening of the disk at larger radii.

THE GALACTIC CENTER

Within the inner few hundred parsecs of the Galaxy one has an enormous reservoir of neutral gas. As is clear from maps of the radio continuum, this gas is being processed in a variety of ways which are unique to this portion of the Galaxy, resulting in a variety of prominent (continuum) structure extending both along and perpendicular to the galactic plane. Mapping of the molecular and atomic gas in the nucleus with existing instruments has allowed us to sketch the broad outlines of these phenomena but has not sufficed to trace the structure in sufficient detail that any overall picture of the history and evolution of the nucleus may be traced.

To specify the pattern of behavior in the nucleus, higher resolution maps of HI are required. HI samples more of the gas and more of the velocity field than does CO (or other tracers of the denser gas portions) and can, through observations in both absorption and emission, provide direct spatial information on front-back placement of various gas components. Yet, the observations must be done with an instrument which provides good spatial resolution (to separate discrete continuum sources) and has exceptionally clean beam characteristics (so that weak features can eliably be believed to lie where they are found, and so that continuum sources do not appear in the sidelobes, distorting both the baseline and emission patterns).

THE DISK OF THE MILKY WAY, INTERIOR TO THE SOLAR CIRCLE

The low-z behavior of gas in the Milky Way has been surveyed many times. Unfortunately, knowledge of the distribution and quantity of atomic gas in the "normal" disk is subject to inherent uncertainties which have by and large obfuscated such important questions as the placement of spiral arms in the disk and the degree of segregation of the neutral gas (or other tracers) into them. Use of a modern instrument with improved spatial resolution and lower system temperature will provide much useful information, but cannot be said to provide revolutionary capabilities in this area. We will achieve a more precise specification of the galactic velocity field due to improved signal-noise, baselines, and elimination of stray radiation, and can expect to "see" more clearly the small but systematic deviations of the gas from a single planar layer. Improved spatial resolution will also help to separate the vertical structure of the several components of the neutral gas, and perhaps provide details of the association between atomic and molecular gas in giant cloud complexes throughout the disk.

WARPING AND FLARING OF THE GALACTIC LAYER BEYOND THE SOLAR CIRCLE

At galactocentric radii greater than that of the Sun, the thin central layer of gas in the Milky Way exhibits two unusual phenomena. It becomes progressively thicker and shows a coherent warp which lifts it progressively further away from the plane defined (and very clearly so) at smaller radii. The cause of the warp is unknown, although speculation centers on an encounter between the Milky Way and one of the companion Magellanic clouds.

Beyond this, the mechanism which has maintained the warp is perhaps even more mysterious, as it might normally be expected in a largely planar system that strong forces normal to the galactic plane provide a strongly confining influence. Clearly, the coherence of the galactic warp provides strong "hints" about the form of the underlying gravitational potential across the Galaxy.

To specify these phenomena it is necessary to map large regions of the sky with very high sensitivity (because the behavior in question is subtle, being of low column density and limited to a small region of the line profile), with great confidence in the telescope's ability to separate direct from stray radiation, and with sufficiently high angular resolution that (often) very distant gas can be traced with some degree of clarity.

HI AND WORK AT OTHER WAVELENGTHS

Recent space missions have and will produce IR and X-ray data whose interpretation needs 21 cm line data of better angular resolution than currently is obtainable over most of the sky. The IRAS satellite has mapped the 100 micron IR emission from diffusely distributed dust over the sky, and the dust that produces this emission is intimately associated with HI. Soft X-ray mapping of diffuse soft X-ray emission, in the past by rocket-borne detectors and in the future by several satellite-borne detectors, provides the only information on the > ~ 1E6 K gas that is supposed to occupy large fractions (~50%) of the interstellar volume. And all X-ray observations of sources are absorbed the intervening medium, so knowledge of the HI column density on reasonably small angular scales is required for its interpretation.

In the IRAS data set, comparison of the HI and IRAS data shows differences that almost certainly point to the existence of molecular hydrogen (H_2) even at low total column densities. Heiles, Reach, and Koo (1988) have shown that this situation occurs in about 30 percent of the high-latitude clouds they sampled. Verschuur (1988) finds angular displacements of HI and IRAS peaks, and this is most straightforwardly interpreted in the same manner: IRAS shows the total column density, HI plus H_2, while the 21-cm line shows only the HI. Angular resolutions of the same order as the IRAS resolutions are crucial here; IRAS resolution was about 3 arcminutes at 100 microns, and 21-cm line resolutions worse than about 8 arcminutes would not be useful for such studies.

There is ample evidence for the overall correlation of IRAS and HI emission, and some additional evidence for the effect of gas dynamic interaction on grain size distribution (HBK 1988). This comes in the form of a change in the IRAS spectrum of the dust emission with the velocity of the HI: rapidly moving HI has a higher 60/100 micron ratio. This implies hotter, and therefore smaller, grains. Rapidly moving HI also has a smaller 12/100 micron ratio, which implies the absence of the very small grains that emit at 12 microns by quantum fluctuations. The most reasonable interpretation is that the grain size distribution has been modified by shocks. The detailed study of the structure of these shocks, both in HI and IRAS, would reveal much about the evolution of grains WITHIN the shocks.

Soft X-rays are absorbed by the interstellar medium. For 150 ev X-rays, an HI column of only $1E19^{-2}$ provides optical depth unity. Thus, accurate HI column densities are essential to correct the X-ray measurements for the intervening absorption. Accurate measurements of such low column densities are limited by "stray radiation," i.e., by weak, distant sidelobes of typical parabolic reflectors. These are produced mainly by aperture blockage by structures such as feed legs. Other deleterious instrumental effects are nonflat baselines, which are produced both by standing waves in the telescope-feed structure and by scattering of solar radio emission into the feed from distant sidelobes. Finally, reasonably high angular resolution is required so that the HI column density can be determined at the position of the source of interest. These requirements argue for an unblocked aperture and an angular resolution of $< \sim 9$ arcminutes.

INTERSTELLAR MEDIUM

The study of large numbers of high-latitude HI clouds with reasonably high angular resolution would be of immense interest for the overall topic of interstellar gas dynamics and the thermodynamic properties of the gas. These structures are really radiative shocks. Radiative shocks probe the thermodynamics of the gas, because the temperature depends on the balance between cooling and heating rates as the gas cools behind the shock. Theoretically, cooling should occur over a column density of ~1E20 behind the shock, although this depends on both shock velocity and the degree to which carbon is frozen out on the grains. Measurements of this column density would test these theories and determine the cooling properties. These studies require reasonably high angular resolution for the rapid accumulation of data on large numbers of these objects for statistical studies. In addition, studies at much higher angular resolution are required, at least in some cases, to observe the detailed structure of thermal instabilities that should exist in these regions. These studies can be done only at the VLA. [Our big telescope would act as a "finding telescope to pick out the best such regions for detailed study.]

The radiative shocks should produce regions with very high densities. Indeed, the comparison of HI and IRAS, mentioned above, that delineates regions containing H_2 are probably just these regions of high volume density produced by radiative shocks. However, Zeeman studies of the HI have shown that the radiative shocks are, at least in many cases, pressure dominated by the magnetic field. This prevents the large density buildup. It would be most interesting to compare magnetic field strengths and volume densities behind radiative shocks. Following the reasoning presented so far, we might expect regions where IRAS and HI do not correlate well in detail to be regions where substantial quantities of H_2 exist--i.e., high density regions-is precisely opposite to common knowledge, although some observational evidence for it exists in some regions, such as the absorbing clouds in front of Cas A (Heiles and Stevens 19__). These studies require the ability to perform highly accurate measurements of circular polarization, to measure the Zeeman effect with angular resolutions equal to that of the HI mapping resolution, which itself should not be too much worse than the IRAS resolution at 100 microns.

Magnetic field studies are also important in dense clouds. They can be done from Zeeman splitting of either the 18-cm OH line seen in emission or the HI line seen in self-absorption. The latter is strong and easily detected, at least in some clouds, while the former is very weak and requires very long integration times. Both are important, because they sample somewhat different portions of the cloud and sometimes give different results. Studies to date have shown that magnetic fields and kinematic motions are in rough equipartition, and together are in rough virial equilibrium and self-gravity (Myers and Goodman 1988). We would like to go further and test theories of star formation that rely on the magnetic field to determine whether low mass or high mass stars are formed and that rely on the field to get rid of the angular momentum during the star formation process. This requires the observation of a sizeable selection of clouds, together with the mapping of the magnetic fields within the clouds in both OH and HI.

Astronomers tend to concentrate on the bright clumps: clumps are interesting in themselves and easy to study. However, the edges of clouds are fascinating places because they are the interfaces between the cold neutral matter (CNM) of the cloud and whatever lies outside. For the environment, there are three candidates: one, the warm neutral matter (LWNM); the warm ionized matter (WIM); and the hot ionized medium (HIM). Here "warm" means ~1E4 K and "hot" means ~1E6 K.

The character of the interface should differ for the three types of outside matter. WNM is similar ion ionization state to the CNM, and in addition is directly observable in the 21-cm line itself. Indeed, the study of CNM/WNM interface regions is part of what we have been discussing in our above descriptions of HI mapping. The WNM is similar to the standard HII region, and the boundary between the WNM and the NM should be sharp and should probably have a large pressure jump which will produce conditions not too unlike those at the edge of an HI region, with its accompanying velocity and density discontinuities. Details of the HIM/HI interface depend sensitively on geometry and magnetic field configuration (ref Balbus), and by studying these details observationally we hope to confirm the predictions of the theory and obtain values of some of the important parameters.

More important for the overall dynamics of the interstellar medium, however, is simply the statistics: What fraction of each kind of interface is there? This would tell us the fraction of volume occupied by each of the WNM, WIM, and HIM--a question of major importance for the large-scale models of the ISM because it depends on supernova rate and the methods by which the supernova energy is dissipated. Studies of large numbers of interfaces would, we hope, reveal a small number of different types of interface that could be classified simply by their appearance as seen in moderate resolution 21-cm line maps.

The above studies place several requirements on the telescope, some of which may be conflicting. One requirement is the ability to measure weak HI emission reliably. This means low sidelobe levels, which argues for a clear aperture. Another is reasonably high angular resolution. This requirement is set primarily by the intrinsic size scale of high latitude HI emission and in addition by the IRAS angular resolution and in addition by the need to define which areas are suitable for more detailed study at the VLA. The angular resolution must be about 9 arcminutes or better; worse than 9 arcminutes is not very interesting, because from previous 300-ft studies we already know that 9 minutes is adequate--but required--for most studies. Another is high brightness temperature sensitivity. Another is the ability to do high quality mapping, which means a clean beam and a beam whose properties are invariant with position.

Finally, the Zeeman effect studies require excellent performance in circular polarization. There are three instrumental effects of concern. One results from far out sidelobes which tend to be highly polarized. These are produced primarily by scattering off objects within the aperture, such as feed legs, and argues for a clean aperture. A second results form the "error beam," which tends to contain beamwidth size peaks that are highly polarized. This requires a good surface at 21-cm and the smallest angular size for the error beam that is possible. This means long correlation lengths for the surface irregularities. Finally, an extremely serious problem arises from offset-fed systems because they produces two circularly polarized beams that do not point in precisely the same direction. The ideal solution, which eliminates all of these, is a technical challenge which, perhaps, is not solvable. If it is impossible to have simultaneously a clear aperture together with an on-axis fed telescope, Zeeman effect studies would probably be better served by the on-axis choice. However, this is in conflict with the clear aperture requirement of virtually all other programs of interest. So from the overall standpoint, we would prefer the clear aperture. This might not be disastrous for Zeeman studies, because IN PRINCIPLE it is possible to correct for the instrumental effects produced by the "beam squint."

Extragalactic Neutral Hydrogen

Technical Requirements

The most important property of an instrument designed for extragalactic HI observations is high sensitivity. This means a maximum ratio of effective collecting area to system temperature. A minimum set of values for a fully steerable antenna is 100 meters aperture with an efficiency greater than 55 percent and a system temperature of 110 Kelvins. An aperture of 150 meters is very desirable.

Interference below 1400 MHz is a severe problem and will get worse. Far sidelobes must be suppressed by at least 10 dB, and preferably 20 dB, below those of the current generation of antennas. Even with this added protection, spectrometers must be designed to handle interfering signals many tens of dB stronger than the minimum detectable signal strengths.

Very good spectral baseline performance is required for high sensitivity spectrometery. Suppression of far sidelobes and a clean reflector structure are required to permit daytime observations of weak hydrogen radiation which has often been hidden by poor baselines in current instruments due to solar interference.

Maximum sensitivity must be maintained over the 700 to 1420 MHz range with relatively little loss down to about 200 MHz recognizing that the sky background temperature will become a dominant factor below 400 MHz. Short term frequency agility is desirable but should not override the desire for maximum sensitivity. Surveys for optically invisible galaxies and neutral hydrogen clouds require as many simultaneous beams on the sky as possible. Receiver packages with seven or more feeds of reasonably high efficiency and low system temperature must be possible with the telescope reflector configuration.

The sky coverage must be +90 to -45 degrees declination with the southern limit being subject to cost trade-offs. A southern limit higher than -40 degrees is not acceptable. Tracking time must be at least several hours around the meridian.

Sidelobes within 20 degrees of the main beam should be 20 dB below the main beam. The ellipticity of the main beam should be less than 0.3 at all declinations and not change substantially while tracking. Pointing accuracy must be better that a tenth of a half-power beamwidth maximum deviation. Polarization purity is a minor consideration. A slew speed greater than 20 degrees per minute and an acceleration rate greater than 5 degrees/minute/second are acceptable in both altitude and elevation. Higher values are desirable.

Rick Fisher

Spectroscopic considerations for the big replacement telescope

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R. Anantharamiah, W. Baan, W. Batrla, R. Brown, G. Knapp, R. Maddalena, R. Rood, L. Snyder, P. Thaddeus, B. Turner and A. Wootten (Chair)

EXTRAGALACTIC STUDIES

Spectroscopic considerations for the design of the replacement telescope are driven by the importance of the observations of molecules, particularly CO, as adjuncts to HI in the study of the interstellar medium and its evolution as the parent glaxies and cluster of galaxies, in turn, evolve.

The evolution of stellar populations in galaxies has been strong over look-back times corresponding to $z \sim 1.5$ to which modern data now covers. Even at redshifts of 0.75 galaxies in dense clusters appear bluer than those in nearby clusters (see review by Oemler, 1986 in Stellar Populations, p. 197, and Gunn and Dressler). Star formation in these systems may occur in massive starbursts, which were probably more intense or more frequent in the past. Of particular interest is the finding that the fraction of ellipticals in the cores of dense clusters, which is essentially 100 percent at the present epoch, has dropped to 70 percent by $z = 0.5$. This means the ellipticals form not only at the first epoch of galaxy formation but until very recent times, and so the hugh starburst which may indicate the formation of an elliptical can be studied both optically and in emission from its interstellar gas. Nearby examples of the starburst phenomenon are targets of intensive current research. Do mergers initiate this process? Does total gas content determine its duration? Are the long term consequences for the host galaxy gas depletion and evolution to a giant elliptical? Stars form in molecular clouds, and answers to these questions will be addressed through study of these clouds. The vital physical parameters--mass, temperature, mean density, star-forming efficiency--of these clouds is measured through CO observations, which currently reach out to $z=0.15$. There is good reason to believe that current instrumentation lies at a threshhold in sensitivity beyond which the observation of CO in galaxies could proceed up to the epoch of galaxy formation, which may have continued as late as $z=2$-3. The increase of sensitivity afforded by a large (50-80m) telescope would push these observations to lookback times when galaxies are thought to be significantly different than they appear today and quite possibly to the epoch of their formation.

Particularly interesting are the host galaxies of QSO's. Strong CO emission has been detected in I Zw I (Barvainis, Alloin and Antonucci 1988, preprint) and Mrk 1014 (Sanders, Scoville and Soifer 1988, preprint), and others are being actively sought. Through the starburst, molecular clouds are thought to create the stellar population which feeds the central engine of a QSO. CO observations with existing telescopes have identified galaxies in these first stages (Norman and Scoville 1988, Ap. J. 332, 124). As the QSO phenomenon has evolved strongly, being more common in more distant galaxies, a large sensitive telescope could reveal many new objects for detailed study. The starburst galaxies and QSO-host galaxies with massive CO concentrations that we now detect with the 12m telescope at redshifts of 0.1-0.2 can be detected only with great difficulty at higher redshift owing to the greater beam dilution at lower frequencies. However, with a telescope as large as 70m diameter galaxies such as I Zw I and Mrk 1014 are detectable in CO at redshifts of 3 [CO(J=1-0) redshifted to 29 GHz] with line antenna tempertures exceeding 5 mK. Not only would a telescope of this diameter be an effective "redshift machine", but such studies would allow us to explore the evolution of the molecular content in galaxies from the epoch of galaxy formation to the present. Frequency coverage from approximately 20 to 100 GHz is required corresponding to redshifts of 0.15 to 6 with only the region $0.7 < z < 1.0$ inaccessible owing to opacity from telluric oxygen.

Study of the spiral structure in nearby galaxies requires very large telescopes or interferometers. Unfortunately, current interferometric observations are sensitive to only one third the total CO flux at best in typical galaxies, measuring only the brightest giant molecular clouds in spiral arms. Interarm gas, even in such fairly active galaxies as M51 (Guelin, Garcia-Burillo, Blundell, Cernicharo, Despois and Steppe 1988, preprint) and much of the molecular gas in less active galaxies such as M31, is weaker in the J=2-1 line than in the J=1-0 line. Studies of this dominant component of the molecular gas must be done in the J=1-0 line, using large antennas.

The chemical evolution of galaxies may be studied via observation of the isotopic variants of CO, ^{13}CO, $C^{18}O$ and even perhaps $C^{17}O$. Since the abundant isotopic form is optically thick, one must rely on the scarce forms to measure chemical changes in galaxies, a task requiring very sensitive antennas with small beams.

Some galaxies, low surface brightness irregulars exemplified by the LMC, are so weak-lined that their study is probably confined to large single antennas for the forseeable future.

The spectroscopy of the ISM in galaxies, then, requires the largest antenna it is feasible to build. An antenna in the 50-80m class would be absolutely unique in the world and, we believe, would offer the most exciting scientific benefits imaginable for a replacement telescope. We envision, basically, a superb centimeter instrument operated with reasonable efficiency at 3mm. The telescope should have excellent receivers over the whole 3mm and 7mm bands since redshifted CO may be detectable at any frequency therein. The telescope should be fully steerable and capable of providing good baseline stability (low blockage). Since good efficiency may be achieved in the inner portions of a larger reflector, for which accurate pointing may pose a problem, array detectors would be of particularly good use. This may preclude use of a shaped surface. The instrument should be versatile enough that opportunities may be seized for CO work during excellent weather yet be capable of reverting to low frequency work under deteriorating conditions at 3mm.

GALACTIC STUDIES

The stellar disk

The galactic OH/IR stars provide an excellent tool for study of the structure and kinematics of the galactic stellar disk. There are probably 10^5 such stars detectable by a 100m class instrument, of which only ~2 x 10^3 are now known (te Lintel Hekkert and Habing 1988). The galactic center region is of particular interest, necessitating good southern sky coverage for the instrument. The particular interest in studying a very large sample of these stars is that since they provide kinematic distance estimates, the three dimensional structure of the galactic stellar disk can be studied as a function of distance from the Galactic center, in the same way that observations of HI and CO gas give the 3d structure of the gas layer. Our Galaxy is the only one for which this can be done--observations of edge-on galaxies give only the projected stellar distribution, which in turn is affected by extinction. The vertical structure of the gaseous and stellar disks contains enormous amounts of information about the nature and distribution of the Galactic dark matter, the history of star formation, the total mass of the Galactic disk (the "Oort limit"), the existence or not of the "thick disk," the scattering of stars by molecular clouds, and the stability of the gaseous disk to star formation. The present sample is not large enough to do this--the intrinsic stellar velocity dispersion (interesting in its own right, of course) means that a sample of about 10^4 stars if needed. Unfortunately, the line of interest, the OH 1612 MHz line, has been practically wiped out by satellite interference. This work has great need for efficient RFI rejection.

Evolved stars

While H_2O is useful primarily as a tag identifying stars for the purpose of measuring their kinematics, SiO maser studies appear capable of providinginformation on the structure of the near-stellar environment. The ground state and J=2-1 transitions at 43 and 86 GHz provide keys to understanding the transition to transition variations in the lines. VLBA baselines are too long to provide information on most of the nearby well-studied maser stars, and much work remains to be done by single antennas.

H_2O emission from evolved stars is a fairly unexplored area. For example, observations of a large sample may well find a number of those rare objects which are currently evolving towards the planetary nebula stage. Some of these stars appear to be expelling molecular gas at speeds in excess of 200 km/sec (Likkel and Morris 1988; Gammie et al. 1989). This area is likely to become a lively one at millimeter and submillimeter wavelengths in the immediate future, and H_2O observations in both provide a complement to these observations and allow the statistics of the objects (and hence the lifetimes in various phases) to be examined.

Cores of dense clouds

With a beamsize of 10"-30" from millimeter to centimeter wavelengths, a large antenna is well suited to studies of the physics of dense cloud cores. Most methods for estimating densities in clouds rely on the determination of the excitation temperature of a particular molecular transition and relating it through the equations of statistical equilibrium to the total gas density via the collisional excitation rates. At centimeter wavelengths, one usefully employs NH_3 and H_2CO to diagnose the temperature and density of cloud cores now; extension to higher frequencies with a larger telescope would open up a number of new diagnostic molecules for use, such as HC_3N, C_3H_2, CH_3OH, HNCO and SO.

For example, HC_3N has several advantages as a density probe (Vanden Bout et al. 1983). At the temperatures and densities typical of cool molecular clouds, numerous transitions are excited and easily observable. The lines are likely to be optically thin, so that problems of interpretation in the presence of radiative trapping effects are minimized. Both these advantages are well-suited to observations of cold moderate-density clouds. At temperatures of 10-20K and densities below $5x10^4$ or so, the strongest transitions of HC_3N are the 3-2, 4-3 and 5-4 lines at 27, 36 and 45 GHz. As illustrated by Vanden Bout et al., the higher lines are quite weak, apparently as a result of a lack of excitation capacity in the clouds.

The C_3H_2 molecule produces a number of spectral line combinations whose frequencies lie close together but whose levels lie at differing energies (Avery and Green 1988, preprint). This attribute makes C_3H_2 an unusually precise species for the determination of physical conditions in dense cloud cores of all temperatures.

Methanol (CH_3OH) displays an extremely rich spectrum ranging from low centimeter to submillimeter wavelength. The excitation of this asymmetric rotor molecule is complex and complicated due to hindered internal rotation and the three-fold symmetry of the methyl group. However, this complexity makes the molecule a extremely useful tool to explore a wide range of physical conditions in molecular clouds.

The detection of strong new maser lines from the 4(-1) - 3(0) E-type transition at 36.1 GHz (Haschick and Baan 1989) and from the 7(0) - 6(1) A+ transition at 44.1 GHz (Menten et al. in preparation) underline the importance of the scarcely explored Q-band - the frequency range from 25 GHz to 50 GHz - for an understanding of the physics in molecular clouds. These lines provided the missing link for an understanding one aspect of the maser phenomenon in methanol. For example: In the molecular cloud towards DR21(OH) the 2(0) - 3(-1) line at 12.2 GHz is seen in absorption against the microwave background since no cm-continuum is associated with the source (Batrla et al., 1987), while the 5(-1) - 4(0) line at 84.5 GHz exhibits a 145 K maser line (Batrla and Menten, 1988). The 4(-1) - 3(0) E line is a maser as well, with an almost identical line shape to that of the 84.5 GHz line. Model calculations of radiative transfer show that this behaviour of three lines out of consecutive J levels in the same K ladder of E-type methanol can only be explained by collisions in a low temperature high density environment (Walmsley et al. 1988).

The detections of maser lines from the 8(0) - 7(1) transition (Plambeck and Wright, 1988) and the 7(0) - 6(1) transition of A+ methanol point towards a similar systematic for this idependent species of methanol. Under completely different excitation conditions, towards compact HII regions, the 12.1 GHz line - seen in absorption against the microwave background in cold clouds - is detected in maser emission at flux densities exceeding those of OH masers associated with the same sources. The multitude of maser lines over vastly different excitation conditions offers a unique chance to unravel the puzzle of maser excitation; the first pieces of which seem to be in place.

All the various masers are embedded in rather weak, compact sources of thermal emission. To fully explore the potential which methanol offers we need observations of high sensitivity, high angular, and high spectral resolution over as broad a range of the spectrum as possible.

A number of molecules such as OH, C_4H, C_2S and SO are particularly well-suited to Zeeman measurements for the estimation of magnetic field strength. It is fundamental to the physics of star formation to assess the importance of the magnetic fields in the dense cores which are about to form protostars. The Zeeman effect is largest at the lowest rotational levels, which lie in the 9 to 23 GHz region for the above-mentioned species. The largest possible telescope is needed to adequately resolve the small star-forming cores at these wavelengths.

Diffuse clouds

Radio molecular observations are particularly important for constraint of diffuse cloud models. Exceptionally narrow components may hide substantial abundances of species, whose chemistry is then misinterpreted on the basis of insufficiently high resolution data (Liszt, 1979). Further investigations (Langer, Glassgold and Wilson 1987) have shown that molecular regions quite commonly have numerous narrow components and an exceedingly clumpy structure. The high velocity resolution necessary to discriminate these components cannot be achieved optically, but is straightforward using radio observations. Problems with current models,e.g. that of van Dishoeck and Black (1986) include discrepancies in the abundances of CO and CH+, for example. Line processes dominate CO photodissociation. Recently measured CO photodissociation rates result, in general, in too little CO. Self-shielding of H2 and CO must be treated correctly in radiative transfer models to address the observed inhomogeneous distribution of molecular material. High spatial and velocity resolution observations must be obtained to refine the models.

One problem in diffuse cloud models has been the high CH+ abundance, which was apparently resolved with the introduction of shock chemistry models. Lambert and Danks (1986) provided strong support for this model by demonstrating a strong correlation between CH+ and excited H2 molecules. Alas, the CO spectra do not show features at either the velocity of the (assumed) preshock gas, or at the broad width expected of the shocked gas. Optical measurements do show a shift of about 1 km s^{-1} between CH and CH+. These two species are chemically linked but should occur in abundance in separate regions, CH+ being created in warm shocked regions while CH occurs farther downstream in the cooled compressed postshock gas. Hence, CH+ lines may be velocity shifted relative to CH lines, and the shift interpreted as a shock signature. However, Lambert and Danks found a mean velocity difference of 0 km s^{-1} between CH+ and CH velocities in their survey. Certainly the optical measurements are difficult and prone to error: the 4300.2 R2 line of CH, for example, is an unresolved doublet. Unfortunately, many of the CH+ lines in the Lambert and Danks survey were also too narrow or too broad to be easily explained by the shock models. One possible explanation, offered by Langer, Glassgold and Wilson, holds that a portion of the CH+ forms in collisions between the cloudlets observed in CO, with a resulting random distribution of CH-CH+ velocities. Clearly there is a need for more accurate CH profile measurements, obtainable with radio telescopes equipped with sensitive receivers, to measure the velocity components in the CH line. Since the CH radio lines occur at 9 cm wavelengths, the largest possible telescope is needed to provide adequate spectral resolution.

Some lines observed in diffuse clouds are stronger than expected, suggesting electron collisions may augment neutral collisions as a source of excitation. Since this phenomenon is more important for molecules with larger dipole moments, the centimeter window is crucial to its study, as the stronger transitions of heavy molecules lie at long wavelengths. While the physics and interpretation of the observations is currently unclear, progress may eventually provide a tool for tracking electron abundance in diffuse clouds.

Astrochemistry

Unlike most other scientific areas which utilize well-chosen but specific molecular lines as probes of the physical conditions in dense clouds, the study of chemistry requires maximum frequency coverage. This is because the most important transitions of different types of molecules, under differing physical conditions, occur at wavelengths ranging from the centimeter to the sub-millimeter. This dependence of spectral features on molecular structure and physical conditions is most easily illustrated for linear molecules, and we choose these species for the following discussion. Non-linear molecules do not behave very differently, but they are more difficult to treat.

The integrated brightness temperature for a given molecular line is proportional to the square of the frequency of the line, multiplied by the population of the initial energy level involved in the transition. For a linear molecule in thermal equilibrium among its rotational energy levels, these two factors result in a transition frequency nu-max of maximum intensity, where

nu-max is proportional to the squareroot of the quantity BT (eq 1).

In Expression 1, B, the rotation constant, is roughly proportional to the inverse cube of the number of heavy (non-hydrogen) atoms in the linear molecule. The frequency of the most intense spectral feature of a linear molecule is proportional to sqrt(B), or to 1/sqrt N^3 where N is the number of heavy atoms. Larger molecules will have their strong spectral features at lower frequencies, viz., toward the centimeter range, whereas smaller molecules will have their stronger features toward the millimeter and even the submillimeter range.

For heavy molecules the strongest lines occur at low to moderate frequency. A glance at Equation 1 reveals that, as temperature decreases, so does nu-max. Hence, the lines are strengthened as rotational dilution is minimized, i.e., the cloud temperatures are cold. This expectation is borne out by recent deep integration at centimeter wavelengths, which have revealed the same sort of spectral wealth previously seen only at higher frequencies in warmer clouds. Thus, the cm spectral region, in addition to playing an important role in the astrophysics of molecular clouds, is now being recognized as highly important in clarifying the astroschemistry as well, a role previously emphasized more for the mm and submm spectral regions.

For several reasons, the 3mm window remains the most important one for the overall study of astrochemistry. The density of lines per unit frequency interval in the 3mm window is such that it can be estimated that ~300 interstellar molecules can be identified before line crowding precludes further identifications. This is to be compared with the 82 presently identified species. By contrast, the line crowding is a factor of several times worse in the higher-frequency windows, as a result both of excitation conditions (at least in the warmer clouds) and of the fundamental nature of the microwave spectra of typical interstellar-type molecules. Thus, fewer species may be identified in these higher windows.

The 3mm window involves excitation conditions which are well matched for most of the 80 known molecules to the actual conditions in a large range of objects ranging from cold cloud cores to warm star formation regions, to hot shocked regions. Yet the weaker line strengths typical of transitions in this window preclude such severe crowding. NEARLY ALL OF THE KNOWN INTERSTELLAR MOLECULES HAVE BEEN IDENTIFIED IN THE 3MM WINDOW. The only exceptions are the diatomic hydrides, whose domain lies in the submm. Of prime importance to astrochemistry in the 3mm region is a very large aperture telescope. Systematic spectral surveys of the 3mm window (Johansson et al. 1985; Cummins et al. 1986; Turner 1989) do not agree all that well at the low levels where many unkown lines and other details important to the chemistry occur. The reason seems to be the complexity of objects such as SgrB2 and Orion, complexity which is not well resolved with current telescopes. The very different beam sizes of the current survey instruments (7m to 20m aperture) thus produce strongly differing results, badly confusing attempts to analyze abundances.

The above discussion has focused on why different frequency ranges are necessary for studying different molecules and/or different physical conditions. Frequency agility is also needed for individual molecules for the purpose of identification. It is difficult to establish the presence of a new interstellar molecule based on a one-line identification. Consider the molecule CH_3C_5N, which we suppose has been tentatively identified in TMC1 via a transition at 20.2 GHz. Confirmation will require observations of other transitions at frequencies spaced every 1.5 GHz. The most useful confirming transitions are ones separated rather widely in frequency, which will provide a measure of the excitation temperature of the molecule and most securely establish its abundance. In addition to the desirability of frequency agility for the purpose of identification, such a capability would be most useful for simultaneous mapping of two or more transition frequencies of a particular molecule in order to determine excitation conditions, and hence abundances.

Rare isotopes of cosmological interest

A large single dish would offer significantly improved opportunities to obsrve two rare isotopes which probe the era of cosmological nucleosynthesis---deuterium (D) and helium 3.

The abundance of D provides an upper limit to the baryon to photon ratio of the universe. Every previous measurement of the abundance---optical or radio---has been surrounded with controversy. The abundance anywhere outside the solar system is probably uncertain by a factor of 10 and even the protosolar value is affected by many uncertainties. One of the most promising ways of determining the D abundance is the 327 MHz hyperfine line of D I. Many recent efforts at measuring this line have been thwarted because of interference. A new very large dish with significantly improved interference rejection should make the measurement possible where the line is found in emission.

^3He can provide lower limit to the baryon to photon ratio and possibly serve as a probe of quark-hadron phase transtion. It also serves as an important probe of the nucleosynthesis of low mass stars. The abundance of He3 can be obtained via the 8.7 GHz of $^3He^+$ (Bania, Rood, Wilson 1988). While this line can be measured with both the 140-foot and the 100-meter at Effelsberg, it is very weak and requires extremely long integrations. A larger aperture should make it possible to measure abundances in many more sources, including planetary nebulae---one of the sites of its nucleosynthesis---and perhaps even extragalactic H II regions. Since $^3He^+$ must be observed in H II regions there is always background continuum. This leads to baseline problems which are one of the main sources of error in current measurments. Thus a very clean beam should lead to significant improvments whatever the size.

In summary, for galactic work a good antenna should have the largest possible size at all wavelengths 100m or so at OH and CH (though this is less critical at the high end) and more than 50m at 3mm wavelength. It should have complete sky coverage, freedom from interference and low blockage. It should be versatile, allowing rapid frequency change and multiband observing capability. For the mapping problems which dominate the science, an array receiver would maximize throughput. It should have excellent polarization characteristics. Furthermore, we note that the backend available to the instrument should be competitive--the current spectral processor is inadequate for the needs we envision.

SOLAR SYSTEM

The cometary OH problem can be important for the new instrument. This emission is weak, suggesting as much collecting area as possible be available. As OH is susceptible to interference, protection is important both in terms of site and instrument design, e. g. low blockage. Comets are most active near the sun, so sky coverage to the southern ecliptic is imperative, but because their orbits are unconfined to the ecliptic, the full sky should be avialable. As comets vary on daily time scales, and their OH emission is extended, an array receiver would be particularly appealing.

Conclusions

We believe that a design providing the equivalent diameter of at least 50 and preferably 70-80m of reasonable performance at 3mm is highly desireable. At lower frequency for spectroscopy (and for the other programs at Green Bank) an antenna with diameter of 100m or more is clearly desirable. Thus we envisage the ''high frequency antenna'' as the inner section of a much larger antenna. We estimate from modest extapolations of the Effelsberg 100m that such an antenna should be possible. To make optimum use of variable weather conditions the instrument should be agile in frequency, covering the range to the 118 GHz oxygen line. It should be capable of acquiring and tracking any object in the Green Bank sky. The telescope design should fully anticipate array receivers and its optics should provide for quick receiver changes and simultaneous multiband operation. The polarization characteristics of the antenna must be excellent. Because of the importance of OH to several projects, both the siting and structure of the antenna should provide maximum RFI and solar protection. This, and the need for stable baselines, suggests that attempts be made to minimize blockage by the secondary support structure.

Arrays

Our committee considered the possibility of an array, and unanimously concluded that this solution is unappealing on many accounts. Many projects are driven by the need for sensitivity. The best receivers are, almost by definition, not cloned. This antenna must have the very best receivers and in practice we have no confidence that the receiver complement on an array could satisfy this requirement. Complete sky coverage is necessary--an array design would have to circumvent shadowing problems. Frequency agility is necessary and the pressure on an array to keep total receiver number low, we fear, would compromise sensitivity. The backend should have several tens of thousands of channels to match the versatility of, for instance, Nobeyama, a stringent constraint on a correlator. Lastly, we fear the enormous operational costs of an array would force compromises in the quality of the instrumentation which would ultimately injure the scientific output of the instrument. This antenna should define the problems to be addressed by arrays. Properly designed, it could be a valuable adjunct to the VLA and the BIMA and OVRO arrays, and further develop the case for a national millimeter wave array.

Appendix

Because we find the most compelling scientific case favors the highest frequencies, the suitability of the Green Bank site was discussed at length.

Geographically, Green Bank benefits from the same Canadian arctic systems which enable observations to be obtained at much higher frequencies at FCRAO, Bell Labs and at Harvard. Additionally, Green Bank is much higher than those sites. Our expectation, therefore, is that it is at least as good.

Atmospheric opacity in the 22 GHz water line is regularly measured during VLBI sessions several times a year. Analysis of this data is under way to provide a quantitative estimate of water vapor at the site.

Radiosondes are regularly launched from Huntington, W. Va., and cover the last 20 years. This data gives a good historical picture of the amount of precipitable water vapor. A tape of the past 20 years of data will be ordered and analyzed using methodology developed by Bob Martin for SMT site selection, and by D. Hogg and F. Schwab for MMA site selection. We expect that the site will be proven adequate, and an effort continues to provide statistics.

Contributions from P. Jewell and others are gratefully acknowledged.

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CONTINUUM RADIATION

J. Condon, J. Broderick, B. Burke, B. Dennison, J. Moran, A. Thompson, and G. Verschuur

1. CONTINUUM SKY MAPPING

Radio continuum sky maps covering most of the celestial sphere with enough sensitivity and resolution to detect large numbers ($N>10^5$) of sources are needed for several reasons:

(1) Discovering intrinsically rare objects. The MIT-Green Bank survey used the 300-foot telescope to find gravitational lens candidates, and only about one source in three hundred is gravitationally lensed.

(2) Detecting radio emission from objects close enough to study easily in other wavebands. Radio source evolution is so strong that only a tiny fraction of radio sources are reasonably local — of the 2×10^4 sources stronger than 150 mJy at 1.4 GHz in the northern hemisphere, only 176 can be identified with galaxies ≥ 1 arcmin in diameter ($\lesssim 300$ Mpc distant) and even fewer are associated with infrared galaxies in the IRAS point-source catalog.

(3) Finding radio sources suitable for high-resolution mapping with aperture-synthesis instruments such as the VLA and VLBA. To study the flat-spectrum radio cores in UGC galaxies, for example, it is first necessary to know which of the $>10^4$ UGC galaxies actually contain such cores. Surveying all of the UGC galaxies with aperture synthesis instruments would require an impossible amount of observing and computing time, but the Green Bank 4.85 GHz sky maps can easily be used to reveal all UGC galaxies stronger than 25 mJy.

(4) Providing a multi epoch historical record of the sky at high frequencies (~5 GHz). All-sky maps show the whole radio sky and are the radio analogs of the Harvard plate collection at optical wavelengths, revealing radio emission (or lack of it) from interesting objects yet to be recognized. Maps covering the galactic plane have also been used to discover exotic radio stars and stellar remnants by their radio variability or flaring on timescales of days.

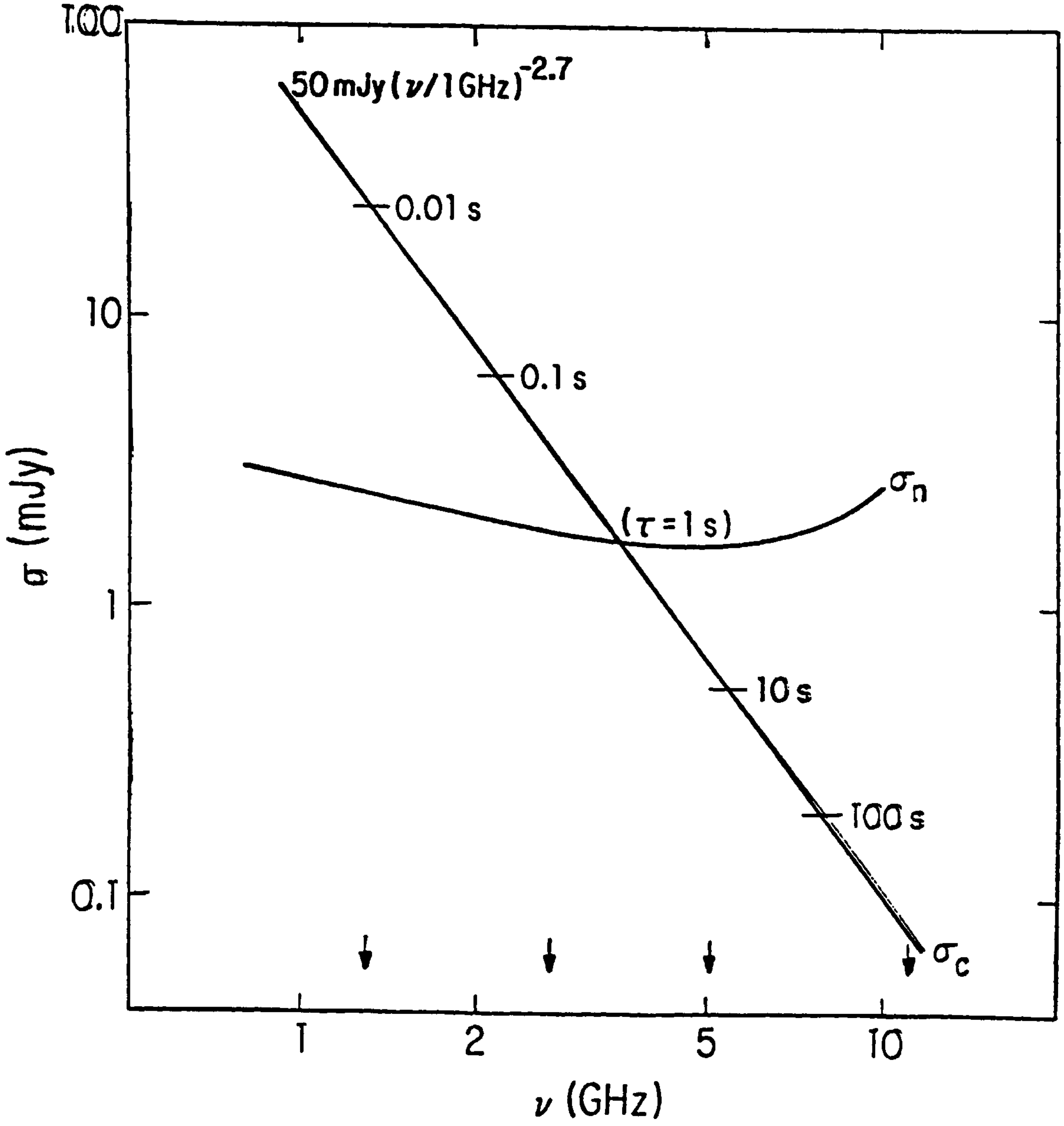
The number of sources that can be detected in a continuum sky survey is limited by receiver noise, confusion, and observing time. For a given telescope size, the rms confusion from unresolved blends of faint sources decreases with frequency approximately as the power -2.7, while receiver noise varies only slowly with frequency as shown in Fig. 1. Figure 1 was calculated for the 300-foot telescope. But confusion and noise are both inversely proportional to telescope area, so changing the telescope diameter only rescales the ordinate; it does not affect the integration times needed to reach the confusion limit. With current receivers and reasonable observing times (<1 year), the greatest number of sources can be detected at a frequency ~ 5 GHz. Even with foreseeable improvements in receiver and feed technology (array feeds producing hundreds of beams, system temperatures ≈10 °K), it is not likely that there will be a need to go above 10 GHz.

The ideal telescope for such surveys would be as large as possible and operate at frequencies up to 5 or 10 GHz. A telescope smaller than 300 feet would be no improvement over the old 300-foot telescope. The new telescope should cover most of the declination range visible from Green Bank ($\delta \geq -45°$ say) but tracking in hour angle could be limited. Multibeaming is necessary to cover the sky rapidly **and** to provide a degree of redundancy for recognizing interference and low-level receiver problems. At most seven feeds fit into the prime focus region of an $f/D \simeq 0.43$ paraboloidal reflector (Fig. 2). At a frequency ~5 GHz this feed configuration fits within a circle <0.3 m in diameter, the inside diameter of a standard Dewar. Larger f/D ratios associated with most subreflector systems may require an unacceptably large feed array and separate Dewars for each receiver channel. Bandwidths of several hundred MHz are used for sensitivity. Interference at 4.85 GHz in such a wide band is not currently a problem in Green Bank, but makes such surveys impossible at Bonn; interference is therefore a concern in the future. Otherwise, extremely low sidelobes are not required. Telescope scan rates of at least 5 or 10 degrees per minute are needed for rapid sky coverage and effective baseline subtraction (to remove long-term fluctuations in receiver gain and atmospheric emission).

2. VLBI

2.1. Improved Sensitivity

The VLBA as a network of 10 antennas will provide images of unprecedented quality because of its excellent uv coverage. However, with 10 25-m antennas (the size dictated by economic constraints), the collecting area is equivalent to only 0.6 of one 100-m diameter telescope. The addition of a single antenna of ~100mwith high efficiency at frequencies up to 22 GHz would greatly improve the capability of the VLBA in several respects. The total collecting area would be increased by a factor of almost 3. The sensitivity of all baselines connecting the Green Bank telescope would be 4 times greater than on other baselines. The data on these sensitive baselines serves to calibrate the instrumental response of each array telescope with respect to the large telescope. Hence, the integration time for the self calibration interval can be greatly reduced with respect to that required for the unaugmented VLBA, thus improving the dynamic ranges of images. Alternatively, with a ≈100m class telescope self calibration can be applied to weaker sources. The ability to phase reference on calibration sources will be improved since with greater sensitivity the angular proximity of calibration sources is smaller. Such VLA style calibration is very important,



100
10
1
0.1
σ (mJy)
50 mJy (ν/1 GHz)^-2.7
0.01 s
0.1 s
(τ = 1 s)
10 s
100 s
σn
σc
1
2
5
10
ν (GHz)

Figure 1

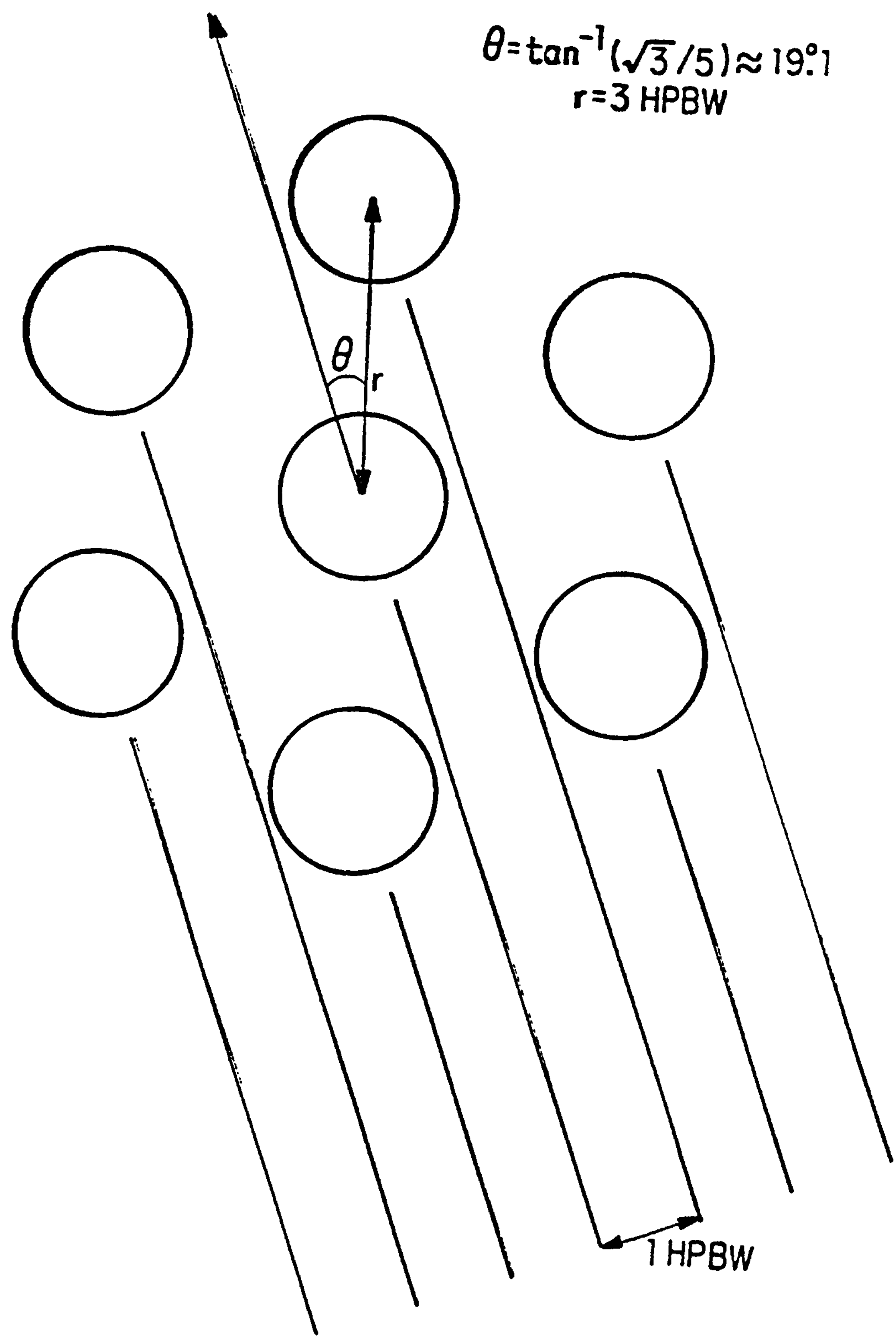


Figure 2

because it makes it possible to extend the coherence time of an array from a few minutes to an indefinite period.

2.2 Science

Increased sensitivity will have a great impact on VLBI studies of weak objects, such as

1. faint structures in superluminal sources
2. gravitational lenses
3. supernovae
4. stars
5. extragalactic H_20 masers.

The first three classes can be studied at centimeter wavelengths, but H_20 masers can only be observed at 22 GHz. The proper motions of H_20 masers have been measured in galactic sources and used to probe the gas flow pattern around newly found stars, and to estimate their distances by the method of statistical parallax. The extension of the work to masers in nearby galaxies is of great importance. Extragalactic masers are weaker ($\approx$ 1 Jy) and their proper motions are about 10 microarcsec/yr (compared to 1 milliarcsec/yr for the maser near the Galactic Center). Such measurements will be very difficult, if not impossible,with the VLBA by itself, but become feasible with the addition of a large antenna and/or orbiting VLBI stations.

2.3. Space VLBI

Japan and the USSR are aggressively moving ahead in their plans for orbiting VLBI stations. Both will probably launch telescopes of diameters ~10m, equipped with receivers at 1.6, 5 and 22 GHz. These telescopes require large ground telescopes to achieve adequate sensitivity. A 100-m telescope linked to a 10-m space telescope would have the same sensitivity as two 33-m telescopes, and hence greater sensitivity than VLBA baselines.

2.4. Special Requirements

The telescope should be able to cover the sky from horizon to horizon, to maximize uv coverage. A phased array would need to have an unblocked aperture in all directions. Slewing and settling speeds may be important to some programs (e.g., phase referencing). Hence slew speeds of 20°/min are desirable so that observations of sources within ~20° can be made within the coherence time.

The added collecting area of the big dish is more important than the uv coverage it provides. However, Green Bank would be an excellent site for a large dish, since it would provide good uv coverage with an array of other large antennas such as the phased VLA, Goldstone and Bonn.

2.5. Surface Accuracy

The exact high frequency limit to the telescope is hard to specify. The motivation to reach 22 GHz with maximum collecting area is strong, because that is the highest frequency planned by space VLBI and it is the frequency of H_20 masers. The VLBA will also operate at 43 GHz and would benefit from greater collecting area. The 100-m dish at 22 GHz is more important than a 70m dish at 43 GHz.

3. VARIABILITY

3.1 Interstellar Refractive Scattering at Centimeter Wavelengths

Recent work suggests that the centimeter-wavelength flux of compact sources is often modulated by refractive scattering in the interstellar medium. The manifestations of this are flickering of compact sources (Heeschen 1984; Simonetti, Cordes, and Heeschen 1985), and relatively rare extreme scattering events (ESE's) (Fiedler et al. 1987).

Flickering is most probably refractive scintillation. The nature and distribution of the turbulent, ionized gas that is responsible are not well understood. Recently, Heeschen has found quite rapid, strong variations in several sources seen through galactic loops, using the 100-m MPI telescope.

ESE's appear to be strong focusing events. The associated abrupt flux changes can be interpreted as the passage of a caustic surface. Essentially nothing is known about the nature of the focusing structures in the ISM, except that the column density of ionized gas varies greatly on au scales. Very probably these structures are filaments or sheets of dense ionized gas, in which case an ESE occurs at the time of a rare alignment of the structure along the line of sight to a compact background source. An appealing hypothesis is that the focusing occurs in cooling substructure in interstellar shocks (Romani 1988).

There is accumulating evidence that ESE's and possibly flickering do not occur uniformly over the sky, but may be found preferentially in the direction of galactic structures such as loops in the nonthermal emission and HI (c.f. Romani 1988). If verified, this would mean that such phenomena could be found more readily by examining sources over limited regions of sky, although this would necessarily involve weaker populations of sources. Therefore, one can envision conducting a monitoring survey of a limited number of such sources in these regions of the sky, in order to identify those sources having active lines of sight and to find ESE's. Because most of the sources are weak, a sensitive telescope at centimeter wavelengths would be required. ESE's when detected should be followed up immediately with a broad range of observations including VLBI, line absorption, and accurate flux and polarization measurements, the latter category requiring a sensitive telescope at centimeter wavelengths with frequency agility and reasonably good polarization purity.

The VLA can and does perform some of the above-mentioned observations, particularly the follow-up continuum and 21-cm absorption measurements. A new instrument would probably be most valuable for performing monitoring surveys of fairly weak sources over interesting regions of the sky.

3.2. General Monitoring Programs

In the foreseeable future, extensive monitoring programs will probably not be a major driving force behind a new general purpose instrument. At centimeter wavelengths, experience with the Michigan and NRL programs has shown that the greatest progress can be made with high-time resolution using dedicated telescopes. This has resulted in substantial information concerning intrinsic variability, the discoveries of polarization rotations in outbursts, and ESE's. Also, the NRL program has accumulated daily measurements over timescales > 3 years. This database is being used to analyze temporal properties of flickering. The recent six-month 300-foot program which detected several ESE's is also an excellent database that is being used to analyze the distribution of flickering sources on the sky. These databases and the large Michigan database can only be significantly augmented with extensive observations using dedicated telescopes. Quite possibly, a centimeter wavelength instrument in Green Bank would be used to augment the frequency coverage of large ongoing programs, as the Michigan group was doing with the 300-foot. Any such augmentation would probably involve frequencies below about 5 GHz, in which case the timescales would be sufficiently long that a general purpose national facility can be used to great advantage.

Low frequency (< 1 GHz) variability appears to be a combination of intrinsic changes and extrinsic refractive scintillation. Further work will probably be directed towards disentangling the two where possible, and characterizing the relevant intrinsic source properties, and the properties of the interstellar medium. In this case the timescales are longer, and the existing databases were collected using a dedicated instrument at a single frequency (Bologna) and two National facilities at multiple frequencies (VPI/UPR/NRAO). Further programs of this nature will probably not be a major driving force underlying the design of a new instrument. They would, however, require a large (~100m) aperture, minimal solar RFI (which is typically scattered into the system by the feed support structure), and protection against man-made RFI below several GHz. Indeed, these properties, combined with frequency agility, and moderate to rapid slew speed characterize the overall instrumental requirements of the monitoring programs.

Although monitoting programs are not foreseen as a primary driver in the telescope design, their importance should not be diminished. The centimeter-wavelength monitoring provides a valuable record of source activity, that can be used both to support other studies (e.g., VLBI), as well as to interpret source evolution. Also at centimeter wavelengths, frequent monitoring can be used as a patrol for ESE's which can then trigger other investigations, such as VLBI, polarimetry, precise flux measurements at multiple frequencies, and line absorption studies. As mentioned above, a sensitive general purpose instrument could provide a valuable augmentation. At low frequencies, monitoring should continue. This will support planned VLBI observations designed to detect the refractive distortions expected on the basis of scattering models. Interpreting such VLBI observations will require detailed knowledge of the low frequency light curves of a number of sources. Low frequency monitoring will require an instrument with large aperture, such as Arecibo, or a large aperture telescope in Green Bank.

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4. COSMIC MICROWAVE BACKGROUND

Small-scale angular variations in the cosmic microwave background are important indicators of how galaxies and clusters of galaxies form. In "standard" theories density fluctuations with mass M at recombination cause temperature fluctuations in the microwave background on angular scales, angle $\sim M^{1/3}$. The fractional temperature fluctuations are predicted to saturate at some low value delta T/T $\sim 10^{-4}$ to 10^{-5} for angular scales ≥ 10 arcmin, the angle subtended by masses $M \approx 10^{15}$ solar masses, because larger masses are opaque. Delta T/T is smaller below ~10 arcmin, being roughly proportional to the angular separation for commonly assumed density perturbation spectra and other model-dependent parameters.

Detecting these small temperature fluctuations requires very long integrations with a filled or nearly filled aperture (for good surface-brightness sensitivity) at wavelengths ≤ 2 cm (to escape confusion by discrete sources and the galactic background). Since the rms antenna temperature uncertainty produced by confusion is nearly independent of telescope size, a fairly small ($D \simeq 10$m) dedicated telescope (for long integrations) at a superb site (e.g., Antarctica) appears to be best suited for detecting the strongest expected fluctuations on scales exceeding about 10 arcmin.

Even so, the microwave background fluctuations are so important and the theoretical models are so uncertain that a large (diameter ≥ 70m) steerable telescope operating at wavelengths ≤ 2 cm in Green Bank might make useful measurements on angular scales 1-10 arcmin.

A large steerable telescope operating shortward of about 2 cm would certainly be useful for mapping temperature decrements in the microwave background produced by Compton scattering in the hot intracluster medium of rich galaxy clusters (the Sunyaev-Zeldovich effected). The observing requirements are similar to those described above, except that resolutions ≤ 1 arcmin are needed to resolve individual clusters. Accurate measurements of the Sunyaev-Zeldovich effect in a number of clusters observed in x-rays may yield information about both the intracluster medium and the value of the Hubble constant.

5 . LOW-FREQUENCY POLARIZATION MEASUREMENTS OF THE GALACTIC BACKGROUND RADIATION

5.1 Science.

High resolution measurements of the polarization of the galactic background radiation at 408, 465, 610, 820, and 1400 MHz allow Faraday rotation and the field direction in the local spiral arm to be mapped. When combined with HI emission measure data, the polarization observations give information on the scale-lengths of the depolarizing medium as a function of position on the sky. Preliminary indications are that scale lengths of 1 pc in the plane and up to 20 pc at $b=+40°$ are revealed in the available data, which are related back to the 408 MHz beam of 2.°3 used in the Dutch surveys. Depolarization appears to be associated with structure in the stellar distribution within Gould's belt. Test observations with the 300-foot (beamwidth = 34') showed that unresolved structure with polarization temperature of more than 3 times that found with the 2.°3 beam is present in the North Polar Spur and in the region of high polarization around $l=140°$. Limited 48' data from Jodrell Bank have revealed the presence of an ionized trail created by a Be star with large proper motion.

A 22' beam (150 meter dish) will resolve the Faraday rotation effects produced in Strömgren spheres around B and A stars out to distances of several 100 pc and O stars to several kpc.