LINE INTERFEROMETRY

Ad Hoc Meeting, Green Bank, August 1-2, 1968

G. Westerhout, Chairman

At the invitation of the Director of the NRAO, a group of radio astronomers met in Green Bank to discuss the future needs of spectral line radio astronomy, especially with regard to the present and future availability of interferometers and arrays. Although the group was asked to address itself to the problems of the VLA and the Green Bank interferometer, it chose to discuss the problems on a more general basis and put before the astronomical community some of the most urgent problems in line radio astronomy requiring high resolution and large collecting area. The group also made specific recommendations concerning the use of the Green Bank Interferometer. The group concluded 1) that many astronomical problems in spectral line work are urgently in need of solution; 2) that these solutions will require large amounts of observing time because of the narrow bandwidths and low brightness temperatures generally encountered; 3) and that therefore considerable requests for observing time on existing and future interferometers and arrays can be expected. 4) It also recommended that the NRAO interferometer be equipped with a full complement of spectral line equipment within the next two years.

The following report was compiled by the radio astronomers attending the meeting:

B. G. Clark - NRAO	M. L. Meeks - MIT	G. L. Verschuur- NRAO
D. D. Cudaback- Berkeley	M. S. Roberts - NRAO	S. Weinreb - NRAO
C. E. Heiles - Berkeley	D. H. Rogstad - Caltech	G. Westerhout - Maryland
D. E. Hogg - NRAO	G. A. Seielstad- Caltech	
F. J. Kerr - Maryland	B. E. Turner - NRAO	

Unable to attend were A. H. Barrett (MIT), B. F. Burke (MIT), A. E. Lilley (Harvard), G. Stanley (Caltech) and D. R. W. Williams (Berkeley).

I. ASTRONOMICAL CONSIDERATIONS

Ia. Studies of Small-Scale Structure of the Interstellar Medium

Present knowledge of typical small-scale structure of HI comes from data obtained with the 300-foot antenna. These data indicate a direct correlation between brightness temperature and angular size, almost as though clumps of various sizes have nearly the same density. Unfortunately, however, this places severe requirements on sensitivity: objects of a few minutes of arc in diameter will have brightness temperatures of only about 0.5 ^{o}K unless a new regime is reached in which condensations have more nearly constant mass than density. But in view of recently obtained HI lunar-occultation data this possibility is unlikely.

The properties of condensations in more specialized regions, such as in HII region boundaries, near strong radio sources, and in interstellar shock waves (found with single-beam HI surveys), will be different and it will be of utmost importance to compare them with the properties of the typical interstellar condensations. We would like measurements in perhaps 200 well-chosen regions. Any many-element array would require several weeks or even months per region to reach a minimum detectable brightness temperature of 0.5 ^{o}K with 1 minute of arc resolution.

Absorption measurements against extended sources (in the context of large arrays, this means sources with diameters less than several minutes of arc) will surely prove to be interesting. Interferometric absorption data presently yield structural sizes of a few minutes of arc; we can eventually look forward to surveying perhaps 200 sources with the greatest possible angular resolution, say 5-10 seconds of arc. Sensitivity requirements here are less than in the emission case. Any many-element array can measure an optical depth of 0.02 with 1 minute of arc resolution in front of a 1' diameter continuum source in much less than one day. But only the brightest sources will provide a background for 6" resolution, and several weeks per source will be needed to measure an optical depth of 0.02.

The study of recombination lines in HII regions yields information on electron temperature, electron density and velocity fields as a function of position within an HII region, but to estimate the magnitude of non-LTE effects two, or preferably more, lines should be examined. Of course, the relative strengths of transitions with $\Delta n = 1$, 2, and possibly even 3 will help too. Of special importance is measurement of helium-recombination lines to compare thermal- and macroscopic-velocity fields and the effect of pressure broadening with position. Measurement of the "carbon" lines will yield information on their basic properties as a function of position. It will also be extremely interesting to compare HI and HII densities and velocities near the edges of HII regions. Recombination-line-sensitivity requirements vary widely because the surface brightness can be a very strong function of position, but for strong HII regions such as Orion A at 5000 MHz the peak line brightness temperature is about 5 ^{o}K. With 100 kHz bandwidth an observing time of less than one day on a many-element array is adequate to obtain accurate line profiles with a resolution of one minute of arc; but with the resolutions sufficient to discern structure on the scale of seconds of arc, which we know exist from optical photographs, much more time would be required--as is the case for the more typical weaker HII regions. We could easily occupy a line array for many years in the study of recombination lines alone.

OH in dust clouds has a brightness temperature ranging from 1 to 50 ^{o}K. The more interesting objects at present are the weaker ones, which have structure of brightness temperature 0.5 ^{o}K with 1.8 kHz bandwidth. For a resolution of 3 minutes of arc such a region could be examined with a many-element array in a few days or weeks observing time, but to obtain higher resolution -- which, judging from optical photographs of dust clouds, would probably be fruitful -- would take very much more time.

Most of the precise observational data required for an understanding of anomalous OH emission is lacking. Its physical relation to the small-scale structure in the continuum, recombination lines, and neutral hydrogen is relevant to the question of the excitation mechanism. The proximity of OH emission to protostars or other peculiar objects needs to be studied. High-resolution mapping of the OH emission, which in some cases appears to be extended on single dish measurements, will help to decide whether the OH is associated with the continuum sources at all, or is in foreground clouds whose size can then be determined.

The spatial relation between different OH features or groups of features in a "single" OH source is important in the understanding of non-linear effects in propagation of the line radiation. It is also observationally important: a case exists at present in which a triplet of features appears with the classical right-hand circular, linear, and left-hand circular polarization pattern of the Zeeman effect. But only if the lines arise from the same position on the sky can it be so interpreted, thereby yielding a measurement of a very large magnetic field. Is the polarization of lines a function of position? If so, can it be interpreted as caused by a systematically varying magnetic field, or must its variations be random?

Because they are generally intense and of small spatial extent, anomalous OH emission lines pose no signal-to-noise problems, and in supersynthesis, sidelobes are of no consequence. The relevant range of spatial resolution varies from several minutes of arc for the separation between different emission regions associated with a given continuum source, to a fraction of a second of arc for the size of some emission spots. While the latter is a province of the VLBI, all baselines presently available on the NRAO 3-element interferometer and the Owens Valley 2-element interferometer are directly relevant for the former. Positions to a few seconds of arc have already been achieved with a 480-meter baseline. The frequency resolution required ranges from 500 Hz to 6 kHz.

The same parameters as mentioned in the discussion of H-line absorption are also suitable to the study of the spatial structure of OH in absorption. The information gathered here will consist of the distribution of optical depth of OH in amount and in velocity across the area of a continuum source. Will this present a picture similar to that given by a corresponding HI measurement on the same source?

Ib. Studies of Large-Scale Galactic Structure

There are several approaches to the study of galactic structure which require the capabilities of a large array. These include:

(1) Recombination-line sources: the detection of as many of these as possible throughout the whole Galaxy, and measurement of their velocities and angular sizes, in order to map the distribution of HII regions.

(2) HI absorption measurements in as many sources as possible in order

to locate hydrogen concentrations along the line of sight, and to assist in resolving distance ambiguities.

(3) Magnetic-field mapping through Zeeman measurements of absorption and emission features.

(4) High-velocity hydrogen cloud studies: whether these are part of the gross picture of galactic hydrogen, or extragalactic, they are important to large-scale structure considerations.

The first two of these require a large collecting area. It is important to note that arrays provide large collecting areas at a relatively reasonable cost. (The proposed Owens Valley Array, for example, has a collecting area equivalent to that of a single dish with a diameter of 360 ft.; the proposed VLA has twice this collecting area, i.e. that of a 500-foot dish). The maximum resolution of 1' which has been generally discussed would be quite satisfactory for these problems. The primary requirement in the third problem is resolving power, and again 1' would appear to be satisfactory. This resolution is equivalent to that of a single antenna of diameter 2900 ft!

High resolution (say 1') is desirable in looking for fine structure condensations in the high-velocity clouds, as the presence or absence of these will help to decide between the galactic and extragalactic hypotheses. For this problem, a system is needed with 1' resolution and $T_{B,min} = 0.5\ ^{o}K$.

Normal OH emission of the type which has been found over moderately large areas may also be an aspect of the gross picture. New approaches, such as the discovery of a new line of sufficient strength for large-scale structure mapping, could greatly change our whole present viewpoint, especially if this line could be detected in the background ionized hydrogen throughout the disk.

The classical approach of looking at 21-cm emission profiles does not appear to require very high resolution for large-scale structure studies.

Ic. Studies of Large-Scale Structure in Extragalactic Systems

Hydrogen-line observations of other galaxies will act as an important and probably necessary guide in interpreting the wealth of data now collecting from line studies of our Galaxy. In addition the relative locations of population I objects, i.e., neutral hydrogen, dust, early-type stars, and HII regions can best be studied in other galaxies.

The present suggestion of systematic patterns in the HI-HII distribution and kinematic-field patterns as a function of galaxy type could be extended to a sample about one order of magnitude larger through the availability of 1 minute of arc resolution. Such patterns, if firmly established, could greatly assist in establishing a picture of galactic evolution.

A much larger number of HI detections and measurements of the radial velocity range in galaxies would be possible because of the increased collecting area. This is especially important for the sample of optically peculiar galaxies, very few of which have thus far been studied.

Progress in the detailed study of galaxies through the 21-cm line can only be made in the future through increased angular resolution -- resolution to at least 1 minute of arc. Such resolution can only be obtained through interferometric techniques. Many problems will require high sensitivity, and therefore large collecting area. This is provided by array-type instruments.

Id. New Spectral Lines

The group realizes that, had it met only a few years ago, the existence of the OH lines and the several recombination lines would not have been known. It is likely that additional lines will be studied in the future, both from regions within the Galaxy and from other extragalactic systems. Furthermore, as better sensitivity becomes available, the known lines will be studied in more distant systems. Array-type instruments will undoubtedly be used extensively for this.

II. OBSERVING TIME REQUIREMENTS

In the table below, some very approximate values are given of the observing time required for the projects mentioned above. These values are only crude estimates (better than a factor of 2), and are meant to give some insight into the large amounts of observing time required for line work. It is obvious that, if this facet of the astrophysics of the interstellar medium is to progress satisfactorily, large blocks of array time need to be reserved for spectral line investigations.

In compiling the table, system temperatures of 100 ^{o}K were assumed. $T_{B,min}$ is the minimum detectable brightness temperature, defined as 5 times the r.m.s. noise. In calculating the observing time in days, it was assumed that full synthesis would be achieved; that one object would be tracked for 8 hours per day; that all possible interferometer pairs would be used; and that moves of elements from one day to the next are permitted. Note that there are 24 hours available in a day, and thus 3 objects could be observed each day.

The two-element interferometer consists of two 85-foot dishes. The Dutch array consists of twelve 85-foot dishes. These instruments are available or will be in the next two years. The Owens Valley Array, if funded, will consist of eight 130-foot dishes. The Very Large Array, if funded, is assumed to consist of thirty-six 85-foot dishes. It is obvious that a two-element interferometer can be used for several highly important studies, especially if full synthesis is not required. At the same time, it is clear that the next step in spectral line radio astronomy requires large arrays.

Object	Resolution	Bandwidth	$T_{B,min}$	Observing time in days			
	(min. of arc)	(kHz)	(^{o}K)	2-elem. Interf.	Dutch array	OVA	VLA
Interstellar condensations (HI)	1	6	0.5	10,000	160	51	16
Absorption (HI and OH)							
10 f.u. Source, 1' diameter	1	6	(τ=.02)	2	1	1	1
100 f.u. Source, 1' diameter	0.1	6	(τ=.02)	12,500	200	64	20
Recombination line in Orion A	1	100	2	40	1	1	1
OH in dust clouds	3	1.8	0.5	3,700	60	19	6
[Ex]tragalactic nebulae (280 pc at 1 Mpc)	1	24	5	50	1	1	1
Extragalactic nebulae (280 pc at 10 Mpc)	0.1	24	5	5,000	80	25	8

III. SPECTRAL LINE OBSERVATIONS WITH A LARGE ARRAY

As outlined above, there are many spectral line observations which require resolutions of the order of 1' of arc with brightness temperature sensitivity of $.5^{\circ}K$, or, as a second case, resolution of 0.1' of arc with tens of degrees of brightness sensitivity. Both the Owens Valley Array and the VLA have the required collecting area and baseline lengths to tackle these problems. The Owens Valley Array would be more flexible with respect to frequency change and, in general, more easily adaptable to line work because of the smaller number of larger antennas, whereas the VLA would offer a factor of two greater collecting area. Either instrument, equipped with front-ends covering the 1400-1720 MHz band, would be a powerful tool for investigating the problems described in the previous sections.

The committee did not recommend that any specific action be taken at this time with regard to the design of spectral line equipment for either array. This is due to the uncertainty in the funding and construction schedule of both instruments. It is important, however, that all aspects of the continuum array design allow construction of a spectral line system.

Some specific problems which appear solvable but need detailed consideration are the following:

1) Array configuration for spectral line observations.
2) Design of low-noise front ends and an L.O. system covering the 1400-1720 MHz band.
3) Design of a reliable, general-purpose spectral line processing system.
4) Consideration of the large amount of data output from the instrument: how can this be displayed and presented to the astronomer for physical interpretation?

IV. THE GREEN BANK INTERFEROMETER AND SPECTRAL LINE WORK. A RECOMMENDATION

The committee concluded that there is a widespread interest in the use of the Green Bank interferometer for line work. Members of the group were particularly interested in the availability, as soon as possible, of an H-OH capability. Although recombination line astronomy was not well represented on the group, it is clear that a number of scientists will want to use a line interferometer for this purpose.

It was realized that an H-OH capability has to wait for the completion of front-ends at this frequency, and of back-ends comprising a large number of channels. Therefore, the committee urges the NRAO to provide such equipment within the next one or two years.

A small number of filter channels for use on the 2703-MHz recombination line is now available. This is an important first step toward a complete spectral line facility for the interferometer. Three correlators are now available; within a year twelve will be available, as well as the possibility to observe the 8045-MHz recombination line.

During the second year H-OH front-ends and a multichannel back-end should be constructed or adapted from existing equipment. Engineering and user experience with the line interferometer during the first year will dictate the form which the multichannel back-end will take. The committee notes that shorter spacings are important for line interferometry; construction of one or more additional observing stations will be required. These should preferably be completed at the same time as the H-OH receiver.

The committee notes with pleasure the reconfirmation by the Cal Tech participants of the availability of the Owens Valley two-element interferometer to outside visitors for H-OH line work. This interferometer is currently (and has been for several years) very successfully engaged in line work; the committee recommends that line investigators at NRAO keep in close touch with Cal Tech to profit from the experience gained there.

The future development of all line hardware and software for the NRAO interferometer will depend, to a large extent, on the interest shown by the users through both suggestions for equipment and requests for observing time. Therefore, users are encouraged to confirm their interest and to make detailed observing requests. An appreciable part of the software design will be the solution of the data-presentation problem, and the committee recommends that NRAO begin consideration of this problem at once, along with the design of the spectral line hardware.

The initial development of interferometric spectral-line capability is a necessary precursor of similar capabilities for a many-element array. New and unexpected observational results should be anticipated from the early use of a limited system, and final design specifications for the spectral line capabilities of a many-element array should remain as flexible as possible.