VLB ARRAY MEMO No. 631

NATIONAL RADIO ASTRONOMY OBSERVATORY
Charlottesville, Virginia

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MEMORANDUM

To: K. I. Kellermann, P. G. Napier, A. R. Thompson, W. M. Goss

From: R. L. Brown

Subject: VLBA Options: Inexpensive 12.2 GHz Addition

Purpose of this Memo

There appears to me to be a compelling scientific case for the VLBA to add the capability to observe methanol masers at 12.2 GHz. I suggest that this be done as an addition to the planned frequency bands of the VLBA. The existence of commercial, room temperature, 12 GHz amplifiers makes this option relatively inexpensive.

The Scientific Argument

The non-VLBI astronomer has some difficulty appreciating the advance that the VLBA represents over the present NUG VLBI facility, and we have had some difficulty explaining it in a few, easily understood, declarative statements. Most recently the NSF Chicago Panel (of astronomers) spent an hour or more struggling with the concept of an array of 10 antennas being superior to the present *ad hoc* array of 14 (or more) antennas. This is understandable: more frequency bands, greater bandwidth, higher dynamic range, polarization purity and reliability (!) are related, at best, in a subtle way to scientific gain as seen by an outsider. OK, let me give you an example of an argument that is perhaps more direct.

A dedicated VLBI telescope such as the VLBA allows us to do astrometry with great precision. The angular resolution of the VLBA (1 mas) expressed as a light travel time corresponds to minutes for nearby stars and less than two hours for any object in the Galaxy. Changes in galactic celestial objects are archived not from one generation of astronomers to the next but from one day, or one hour, to the next. Why can't we do this in VLBI now? Because we cannot establish, and track, the geometry of an *ad hoc* array with astrometric precision.

The VLBA will establish galactic kinematics directly. Observations of the proper motion of galactic radio sources relative to the background extragalactic radio sky will allow us to measure the rotation of the Galaxy as a function of longitude, latitude and, of course, distance from the Galactic center. The apparent proper motion of galactic sources resulting from the earth's motion around the center of the Galaxy is large: 250 km/s at R_o = 8.5 kpc corresponds to 6 mas/year. Proper motion measurements of sources throughout the galaxy will provide a determination of the galactic gravitational potential (distribution of mass), and they will put constraints on the existence and distribution of dark matter in the Galaxy.

What galactic sources should we use? We require sources which are unequivocally galactic, bright, compact, and distributed throughout the Galaxy. Interstellar masers come immediately to mind.

<u>OH Masers</u>. These are abundant and bright. But are they compact? Interstellar broadening at 1.6 GHz is severe in the first quadrant of Galactic longitude. Sgr A^* we know is broadened to 0".8 at L band. Sources beyond the Galactic center are both crucial for galactic kinematics and subject to even greater interstellar broadening. OH is not the proper probe.

<u>H_2O Masers</u>. Water masers are abundant, bright, and compact. At 22 GHz we don't have to worry about interstellar broadening. On the other hand, water masers are notoriously time variable (this both good and bad depending on the investigation--here I'm discussing using the masers for years, 1-10, as probes of galactic kinematics) and often they have their own space motions of 100 km s^{-1} or more making them unsuitable for proper motion studies except in a statistical sense.

<u>Methanol Masers</u>: Abundant, compact, bright and (apparently) stable in time and space, these objects seem ideal as probes for galactic kinematics. Interstellar broadening should be relatively unimportant at 12.2 GHz, and initial observations bear this out, over baselines of hundreds of kilometers anyhow. A recent preprint by McCutcheon *et al.* (attached) summarizes many of the VLBI properties of methanol masers to the limited extent that they are now known.

<u>An Inexpensive VLBA Implementation</u>

It would be a mistake to consider replacing one of the VLBA frequencies with 12 GHz. However, let me suggest that we add 12 GHz at the position on the feed circle presently given to 10.6 GHz at the Pie Town antenna but not, as I understand it, planned for other antennas. Commercial room temperature FET amplifiers are available (at Radio Shack, for instance) at very modest cost, $184 each. Most of the expense is in the feed.

We can do useful science on strong methanol masers with a modest system. Note that if we are observing OH and methanol maser lines 1 km s^{-1} wide and we observe both lines for an equal length of time, then we achieve equal sensitivity (Jy rms) if our 12.2 GHz system temperature is 2.7 times greater than the L band system. This means T_{sys} (12.2) = 2.7 (40) = 110 K, and Radio Shack can do nearly this well.

Science with Methanol Masers

While I haven't seen it, I am aware that Barry Turner wrote a memo describing the science that he could see coming from observations of methanol masers. This should be carefully considered. Taken by themselves, methanol masers are unlikely to unlock any secrets of astrochemistry or star formation. On the other hand, the spatial association of OH, H_2O, and methanol masers and the time variations of each velocity component in one species with respect to that of the others may be crucial in our understanding of the pump mechanism. It would be unfortunate for the VLBA to ignore this possibility.

RLB/j

c: P. Vanden Bout

MILLIARCSECOND OBSERVATIONS OF 12 GHz METHANOL MASERS

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ABSTRACT

Long-baseline interferometer observations, with a fringe spacing ~20 mas, have been made of eight methanol masers at a frequency of 12.178 GHz. These are the highest-resolution observations of such methanol masers, and all eight sources were detected. Comparisons of interferometer and single-dish spectra show that most of the spectral features are reduced in amplitude, but some are unresolved, implying component sizes of <6 mas and equivalent brightness temperatures exceeding 10^{10} K. Limited phase information suggests that the positions of the individual features are clustered in regions with sizes typically 18 mpc (1 mpc = 3.1×10^{15} cm), which are similar to those measured for OH masers.

Subject headings: masers - interstellar medium - star formation

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I. INTRODUCTION

The recent discovery of intense maser emission from interstellar methanol at 12.2 GHz (Batrla et al. 1987; Norris et al. 1987; Koo et al. 1988) has provided a potentially powerful new probe of conditions in star-forming regions. OH and H_2O masers have previously been found to occur in regions of high density, and their association with the earliest stages of star formation is now well established (Elitzur 1982). In contrast, little is known to date of the properties of the methanol masers, but their similarity to OH and H_2O masers in intensity, general location, and complexity of emission suggests that other properties may be common as well.

This paper reports milliarcsecond observations, using a single-baseline interferometer, of eight methanol masers. The interferometer fringe spacing is ~20 mas. Visibility measurements allow us to measure sizes of individual components, and our limited phase information allows us to make a rough estimate of the spatial extent of the clusters of components.

II. OBSERVATIONS

The observations were made on 1988 January 22 and March 22 with the Parkes-Tidbinbilla interferometer (Norris et al. 1988). This interferometer, with a baseline of 275 km, uses the Parkes 64-m telescope and the NASA 70-m antenna at Tidbinbilla connected via a radio link for data transmission. Local oscillator signals are generated from independent atomic standards. Fringes may be seen in real time, a feature which greatly enhances the efficiency and versatility of the instrument. The observations described here were the highest-frequency astronomical observations yet made with this interferometer. Because of the limited amount of time available on the 70-m, we observed most sources for only short periods (<20 min).

For the 70-m and 64-m telescopes receiver temperatures were 180 K and 250 K respectively, telescope sensitivities 1.9

and 4 Jy K^{-1}, and half-power beamwidths 72" arc and 120" arc. Pointing accuracies were about 20"arc on the 64-m antenna and 10" arc on the 70-m.

Calibration using continuum sources was attempted, but a combination of poor weather and uncertain pointing resulted in a calibration factor which gave visibilities of >1. Therefore we have adopted instead a calibration factor based on calculations using system parameters.

III. RESULTS AND DISCUSSION

a) General

The eight maser sources, all of which have single-dish peak flux densities of >100 Jy, are listed in Table 1. Positions accurate to ~30" arc were measured at Parkes by observing the spectrum over a grid of positions centred on the nominal position (Norris et al. 1987; Caswell et al. 1988). Observations of these spectra at three epochs have shown that the majority of the features show little or no variability on a time scale of seven months. The kinematic distances in Table 1 were determined using the velocities indicated and the rotation curve of Clemens (1985) with $R_0 = 8.5$ kpc and $\theta_0 = 220$ km s^{-1}. Because of distance ambiguities within the solar circle both distances are given for some sources. If one of these distances is regarded as being less reliable it is enclosed in parentheses and not used. If there is no basis for distinguishing between the distances both are enclosed in parentheses - these sources were not used in subsequent statistics. Figure 1 shows the interferometer and single-dish spectra, and Table 2 summarizes the results for each source.

b) Component Sizes

Four features from the 309.92+0.48 spectrum with visibility, defined as the ratio of interferometer to single-dish intensities, of >0.7 are apparently unresolved. For a simple Gaussian intensity distribution this implies component sizes of <6 mas, or linear sizes of $<5 \times 10^{14}$ cm at a distance of 5.5 kpc (Table 1). For comparison, OH maser component sizes in W3(OH) have been measured at 2×10^{14} cm (Reid et al. 1980), and H_2O maser component sizes in W51M are 1 to 3×10^{13} cm (Genzel et al. 1981). These values are typical of these two species of masers (Reid and Moran 1981).

All other features have visibilities ranging from 0.04 to 0.62. These low visibilities in many features may be the result of a superposition of two or more compact components having the same velocity and separated by at least 10 mas and which are interfering at this particular baseline orientation, or may be due to individual component sizes which are larger than 6 mas. Longer observations of each source will ultimately determine which of these situations applies. The former must be at least partly responsible, since one result typical of all the sources is the resolution of the interferometer spectra into a large number of components, indicating that blending almost certainly occurs over much of each spectrum. Paradoxically, the apparently clearer separation of features on interferometer spectra, which is a common characteristic, is indicative of the overlap of features in velocity leading to destructive interference (as opposed to addition and blending in single-dish observations).

c) Cluster Sizes

Sufficient u-v coverage was obtained for 309.92+0.48 to allow two-dimensional positioning of four features relative to the strongest feature. The largest separation of these components is 315 mas or 9.2 mpc. The limited hour-angle coverages on the other sources do not give us enough phase information to make detailed models. However, from the rates of change of phase with respect to time for the various features relative to one strong feature, it is possible to estimate relative spatial separations projected on to a line parallel to the u-v vector of the interferometer baseline. An ensemble of randomly oriented features will give a distribution of projected separations which is representative of the true radial distribution of the separations between the features.

Using the distances not enclosed in parentheses in Table 1, we onstructed a histogram of the measured projected separations, from hich we deduce that the methanol masers are grouped in clusters ypically 18 mpc in overall extent. For comparison, the OH and $_2$O maser clusters have sizes usually of <30 mpc, with median xtents of 15 mpc for a large number of OH masers and 9 mpc for $_2$O masers (Forster and Caswell 1988; Norris et al. 1982; see also eid and Moran 1981 and references therein). Thus our measurements ndicate that the physical sizes of methanol maser clusters escribed in this paper are in the same range as for OH and H_2O lusters, perhaps more similar to the OH sizes.

Longer observations of the sources in Table 1, and other sources, re required to measure individual methanol cluster sizes and to ke detailed maps.

IV. SUMMARY

The main results are as follows.

High-resolution observations show that some of the 12.2 GHz methanol maser features have spot sizes of <6 mas. For 309.92+0.48 this corresponds to a linear size of 5 x 10^{14} cm. The brightness temperatures of these features are >10^{10} K, similar to values found for the strong OH masers. Higher-resolution observations are required to determine if the brightness temperatures are as high as 10^{11} to 10^{14} K, which is the range of values for the H_2O masers.

2. The cluster sizes of the masers are ~20 mpc in overall extent, similar to many of the OH and H_2O cluster sizes, but smaller than the largest of those values.
3. The similarity of cluster sizes (and possibly of spot sizes as well) of the methanol masers to the OH and H_2O masers suggests that the methanol masers coexist in the same environment and may have similar excitation mechanisms.

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TABLE 1

OBSERVED METHANOL MASERS[a]

Source	Position (1950) R.A.	Dec.	Centre velocity	Assumed distance	Notes[b]
	h m s	° ′ ″	(km s^{-1})	(kpc)	
188.95+0.89	06 05 54.0	+21 38 40	11.0		
309.92+0.48	13 47 12.7	-61 20 30	-60.0	5.5	1
318.95-0.20	14 57 04.0	-58 47 10	-34.5	(2.0), (10.8)	
323.74-0.25	15 27 53.0	-56 20 44	-50.0	3.0, (10.7)	2
335.79+0.17	16 26 06.4	-48 09 37	-47.0	(3.3), (12.2)	
339.88-1.26	16 48 24.6	-46 03 30	-38.0	3.0	3
345.01+1.79	16 53 18.0	-40 09 30	-22.0	2.3	3
351.41+0.64	17 17 32.3	-35 44 04	-11.0	1.7	4

[a]These sources are from Norris et al. (1987) and Caswell et al. (1988), except for 188.95+0.89 (Koo et al. 1988), 323.74-0.25 (Kemball et al. 1988), and 351.41+0.64 (or NGC 6334) (Batrla et al. 1987).

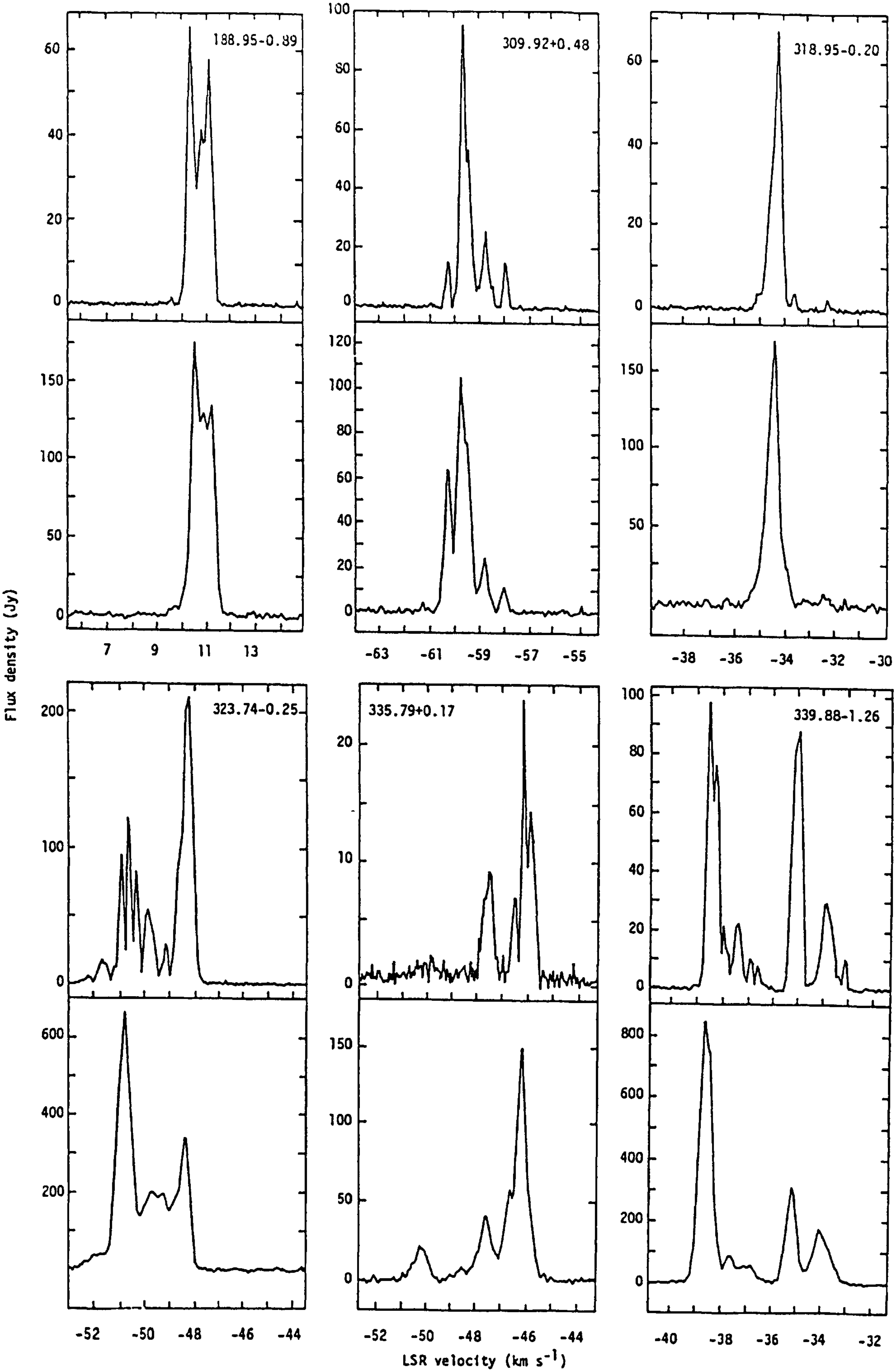
[b]Notes are:

1. The large negative velocity suggests that the source is at the tangent point.
2. Near kinematic distance preferred. The far distance gives the source a much greater luminosity (by a factor of 13) than the other four sources listed with reliable distances.
3. Near kinematic distance chosen because of large |b|.
4. Associated with NGC 6334 (Neckel 1978).

MEASURES VISIBILITIES OF METHANOL FEATURES

Source	Projected baseline ($10^6\lambda$)	Velocity (km s^{-1})	Visibility[c]	Comments
188.95+0.89[a]	6	10.5	0.33	
		10.9	0.32	
		11.2	0.48	
309.92+0.48[b]	9.5	-60.3	0.23	Largest separation of these components is 9.2 mpc (see text).
		-59.8	0.89	
		-59.5	0.71	
		-58.8	1.0	
		-58.0	1.4	This feature has been observed to vary by 50% over one month
318.95-0.20[b]	9.7	-34.6	0.39	Single-dish wing emission at -34 km s^{-1} has been resolved into a narrow component.
323.74-0.25[a]	9.0	-50.8	0.18	Shoulder emission on either side of single-dish feature has been resolved into narrow components.
		-48.3	0.62	
		-49.0→-50.0		This broad emission in single-dish spectrum is resolved into two components.
335.79+0.17[a]	9.3	-50.2	0.04	
		-47.7	0.23	
		-46.7	0.13	
		-46.2	0.16	Broad wing has been resolved into a separate component at -45.7 km s^{-1}.
339.88-1.26[b]	10.2	-38.8	0.12	Shoulder on single-dish main feature at -38.5 km s^{-1} becomes clearly separated in interferometer spectrum. Single-dish wing emission at -38.1 km s^{-1} is resolved into a separate feature.
		-37.7	0.29	
		-37.3→-36.3		This broad emission from single-dish spectrum is resolved into two components.
		-35.2	0.29	
		-34.1	0.17	Shoulder at -33.5 km s^{-1} from single-dish spectrum is resolved into a separate feature.
345.01+1.79[b]	10.6	-23.8	0.14	
		-22.5	0.60	
		-21.8	0.50	
351.41+0.64[b]	10.5	-11.3	0.18	
		-10.4	0.08	Single-dish spectrum feature is resolved into two components.
		-9.8	0.24	

[a]Interferometer spectra observed on 1988 March 22.
[b]Interferometer spectra observed on 1988 January 22.
[c]All single-dish spectra were observed during the period 1988 March 23-28.



188.95-0.89
309.92+0.48
318.95-0.20
323.74-0.25
335.79+0.17
339.88-1.26
Flux density (Jy)
LSR velocity (km s^{-1})

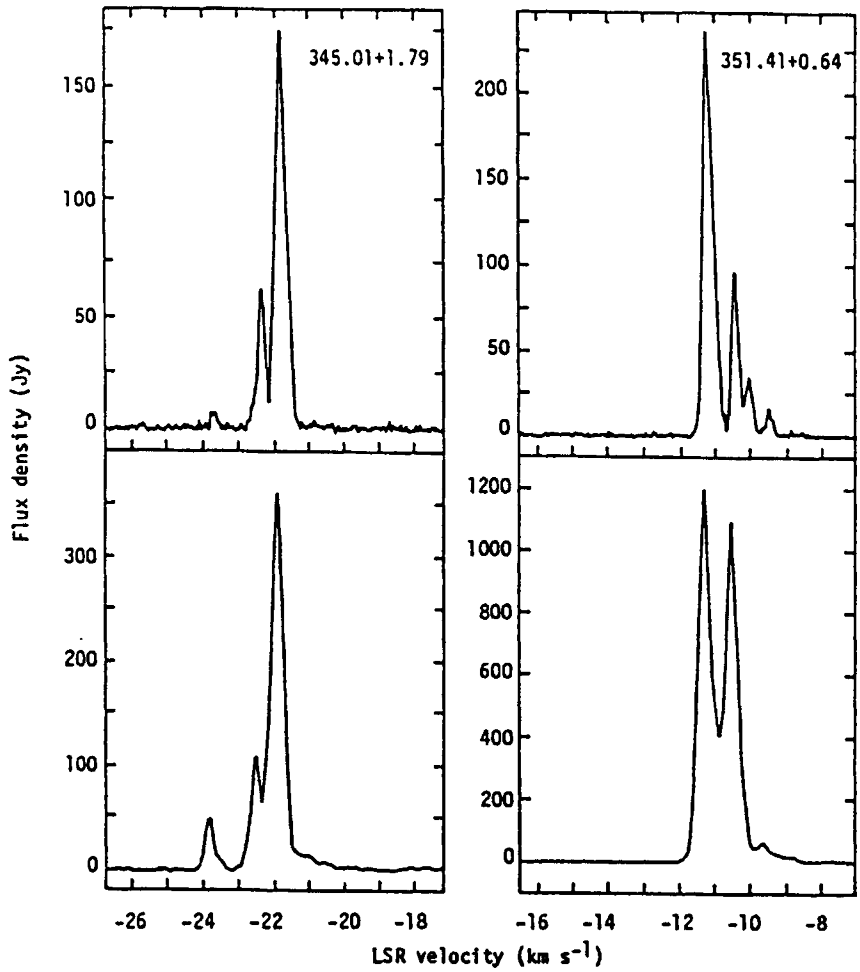


Figure 1 Interferometer spectra (top) and single-dish spectra (bottom) for each of the eight sources. All interferometer spectra have a resolution of 0.06 km s^{-1}, except for the spectrum of 339.88-1.26, which has 0.12 km s^{-1}. All single-dish spectra have a resolution of 0.1 km s^{-1}. The interferometer spectra were observed on either 1988 January 22 or March 22, as indicated in Table 2. All single-dish spectra were observed during the period 1988 March 23-28.