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Methanol masers at 12 GHz

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ABSTRACT

We have searched for 12-GHz methanol maser emission from the direction of 173 OH masers in star formation regions and obtained 53 detections, including 19 previously unreported. The observations of these and four other southern methanol masers are presented. We discuss some of the properties of this extensive uniform sample, in particular the presence of linear polarization and our discovery of intensity variations on a time-scale of weeks.

Key words: masers – stars: formation – ISM: molecules – radio lines: ISM.

1 INTRODUCTION

Observations of several transitions of methanol towards star-forming regions have revealed strong maser emission. The masers fall into two classes, designated Class I and Class II by Menten (1991a), with Class II showing especially intense emission on transitions near 6.6 and 12 GHz. Here we are concerned with the latter, the $2_0 \rightarrow 3_{-1}$ E transition, with rest frequency 12.178595 GHz (Gaines, Castleton & Kukolich 1974). Masers on this transition were first discovered by Batrla et al. (1987), with subsequent searches reported by Norris et al. (1987), Koo et al. (1988) and Kemball, Gaylard & Nicolson (1988). We now present the results of a comprehensive southern survey. These observations of 12-GHz masers pre-date the discovery of masers on the 6.6-GHz transition by Menten (1991b), and thus the survey has not been biased by subsequent 6.6-GHz discoveries.

2 OBSERVATIONS

Observations were made with the Parkes 64-m telescope, chiefly in the periods 1987 July 29 to August 4, 1988 March 21–30, 1988 April 25–30 and 1989 November 11. Most of the masers were observed in both 1988 March and April, and half were reobserved in 1989 November. The equipment was similar to that used in our 1987 April observations (Norris et al. 1987), but with a two-channel receiver that enabled us to record two orthogonal linear polarizations simultaneously. In conjunction with a rotatable feed platform, this facilitated polarization measurements. The receiver was mounted in a feed package at the prime focus and the beamwidth to half-power was 2.0 arcmin. As in our 1987 April observations, the intensity calibration is relative to Virgo A (assumed to have a flux density at 12.18 GHz of 33.5 Jy, or a peak value of 31.4 Jy when observed with a beamwidth of 2 arcmin). Variable weather conditions and other uncertainties limit the accuracy of the intensity calibration to ~10 per cent. The effective system noise of each receiver channel was ~1000 Jy. Spectra of the two polarizations were obtained with the Parkes digital correlator, configured to provide two spectra of 512 channels each. Search observations were made in the 1987 July–August period with 2-MHz bandwidth ($\equiv 49$ km s^{-1}) centred on the OH emission velocity, providing resolution after Hanning smoothing of 8 kHz ($\equiv 0.2$ km s^{-1}). Our sensitivity limit allowed detections as weak as 3 Jy. This detection threshold is a factor of 2 better than in 1987 April, because we recorded signals from each of two polarizations simultaneously, and used integration times of 10 rather than 5 min. Further observations of the detected methanol masers were made using a bandwidth of 1 MHz (and a few additional ones using 0.5 MHz) with correspondingly improved velocity resolution and diminished velocity coverage. These later observations were made on a grid around the detection position to ascertain whether the different velocity features arise from the same location, to estimate the positions more precisely, and to ensure that the intensities were not underestimated by offsets of the source from the telescope pointing position.

3 RESULTS

The initial objective was to search for methanol in the direction of a large unbiased sample of OH masers of the variety associated with star-forming regions. (These are designated 'Type 1' OH masers, a classification scheme totally unrelated to the designation 'Class II' used by Menten for the associated methanol masers that we are investigating.)

The principal search was conducted towards the complete sample of known OH masers in the galactic longitude range 270° through 360° to 60° (mostly from the list compiled by Caswell & Haynes 1983a, b, 1987; Caswell, Haynes & Goss 1980). Of the 180 OH masers searched, seven appear more likely to be associated with late-type stars than with star-forming regions and no methanol maser was found in these directions. 53 of our methanol masers listed in Table 1 are

Table 1. Masers on the 12-GHz methanol transition, located south of declination 22°.

Methanol maser (l,b)	RA(1950) h m s	Dec(1950) ° ' "	Radial (peak)	velocity (range) (km s^{-1})	Peak intensity (Jy)	References & remarks
188.95+0.89	06 05 54.1	+21 39 05	+10.4	+9,+12	178	Bat87;Int
291.28-0.71	11 09 48.2	-61 01 58	-30.0	+29,+32	~3	Nor87;Var;T
305.21+0.02	13 08 07.0	-62 30 03	-32.6	-34,-31	10	Nor87
308.92+0.12	13 39 35.7	-61 53 50	-53.4	-55,-53	9	Nor87
309.92+0.48	13 47 13.1	-61 20 27	-59.8	-61,-57	138	Nor87;Int;LP
316.64-0.09	14 40 32.2	-59 42 35	-19.8	-23,-17	21	Nor87
318.95-0.20	14 57 04.4	-58 47 02	-34.5	-36,-32	174	Int
322.16+0.63	15 14 45.1	-56 27 32	-63.4	-64,-52	21	
323.46-0.08	15 25 28.0	-56 21 07	-66.9	-68,-66	12	Kem88
323.74-0.26	15 27 52.7	-56 20 49	-50.9	-54,-47	530	Kem88;Int;LP
327.40+0.44	15 45 31.0	-53 36 16	-82.9	-84,-82	48	Nor87
328.24-0.55	15 54 07.4	-53 50 53	-44.9	-46,-44	18	Nor87;
328.81+0.63	15 52 01.8	-52 34 33	-46.5	-47,-43	23	Nor87;
329.03-0.21	15 56 41.9	-53 04 31	-37.5	-41,-36	11	Nor87;Double;T
331.28-0.19	16 07 38.2	-51 34 21	-78.9	-84,-77	147	Nor87;Int
335.79+0.17	16 26 05.3	-48 09 35	-46.3	-51,-45	~165	Nor87;Int;Var;T
336.43-0.26	16 30 37.7	-47 59 14	-93.5	-95,-92	22	T
337.61-0.07	16 34 30.6	-46 59 15	-41.9	-44,-40	13	Nor87
337.71-0.06	16 34 49.7	-46 54 55	-54.7	-56,-50	69	Nor87
338.08+0.02	16 35 59.6	-46 35 40	-53.2	-54,-52	20	
338.46-0.25	16 38 35.4	-46 28 45	-52.2	-53,-51	8	
339.62-0.12	16 42 28.0	-45 31 32	-33.4	-35,-31	22	
339.88-1.26	16 48 25.8	-46 03 44	-38.8	-40,-33	780	Nor87;Int;LP
340.78-0.10	16 46 38.2	-44 37 30	-105.4	-107,-98	52	Nor87
341.22-0.21	16 48 41.6	-44 21 53	-37.7	-46,-36	~5.5	Nor87;Var;T
345.00-0.22	17 01 41.0	-41 25 07	-22.2	-23,-21	5	Nor87
345.01+1.79	16 53 20.4	-40 10 00	-21.9	-25,-10	430	Nor87;Int;Double;T
348.55-0.98	17 15 53.6	-39 00 54	-10.2	-11,-9	20	
348.70-1.04	17 16 37.7	-38 55 30	-3.7	-10,-3	25	T
348.73-1.04	17 16 39.9	-38 54 08	-7.5	-9,-6	12	T
351.42+0.64	17 17 32.6	-35 44 12	-11.3	-12,-8	1200	Bat87;Int;LP;T
351.44+0.66	17 17 33.9	-35 42 21	-9.9	-11,-9	81	T
353.41-0.36	17 27 06.7	-34 39 28	-22.3	-23,-19	20	Nor87
354.61+0.47	17 26 59.8	-33 11 46	-16.5	-25,-15	28	Nor87;Var;T
359.62-0.25	17 42 28.5	-29 22 30	+20.2	+19,+24	15	
0.54-0.85	17 47 04.3	-28 53 53	+13.8	+13,+19	~8	Koo88;Var;T
0.65-0.05	17 44 11.0	-28 23 20	+48	+47,+49	>3.6	Whi88;T
8.68-0.37	18 03 21.6	-21 37 42	+44.1	+40,+45	10.5	Koo88;T
9.62+0.19	18 03 17.0	-20 32 03	+1.2	-4,+5	~135	Nor87;Var;T
10.47+0.03	18 05 40.5	-19 52 25	+75.0	+73,+77	17	Koo88;T
11.90-0.14	18 09 14.7	-18 42 21	+42.9	+41,+44	17	
12.03-0.04	18 09 05.5	-18 32 44	+108.5	+107,+110	14	
12.68-0.18	18 11 00.5	-18 02 48	+57.0	+56,+59	12	Nor87
12.91-0.26	18 11 45.3	-17 53 10	+39.5	+38,+41	21	Nor87
15.03-0.68	18 17 31.7	-16 13 07	+21.3	+21,+24	14	Nor87
20.24+0.07	18 24 57.1	-11 16 49	+73.0	+71,+74	5	
22.43-0.17	18 29 59.0	-09 27 32	+37.8	+37,+39	6	
23.01-0.41	18 31 56.2	-09 03 15	+74.9	+73,+84	25	
23.44-0.18	18 31 54.8	-08 33 59	+97.3	+96,+108	12	Var;T
28.83-0.25	18 42 11.6	-03 49 01	+82.2	+82,+84	3	
29.86-0.05	18 43 22.6	-02 48 38	+100.3	+99,+102	14	T
29.95-0.02	18 43 26.9	-02 42 46	+96.8	+95,+98	49	Koo88;T
31.28+0.06	18 45 36.7	-01 29 52	+110.2	+104,+114	114	Koo88
32.74-0.07	18 48 47.5	-00 15 48	+30.4	+29,+39	10	
35.19-0.74	18 55 40.4	+01 36 34	+30.5	+26,+31	44	
35.20-1.73	18 59 12.7	+01 09 15	+44.5	+40,+47	~125	Nor87;Var;T
49.49-0.37	19 21 22.3	+14 25 08	+56.0	+55,+58	14	Bat87;T

Bat87: Batrla et al. (1987); Nor87: Norris et al. (1987); Koo88: Koo et al. (1988); Kem88: Kemball et al. (1988); Whi88: Whiteoak et al. (1988).

Double: two centres of activity separated by ≥20 arcsec; Int: interferometer data, published in McCutcheon et al. (1988) or Norris et al. (1988); LP: linear polarization detected; Var: variable; peak intensity is shown as approximate (~) if it varies; T: discussed in the text, Section 4.2, as a source of special interest.

associated with the remaining 173 Type 1 OH masers. Some additional searches were made at the positions of H II regions and H_2O masers where no OH maser is known. The total of 57 masers in Table 1 includes our previous sample (Norris et al. 1987), our observations of masers reported by Batrla et al. (1987) and by Koo et al. (1988), and 19 masers newly discovered in the present search. Positions quoted in Table 1 are from our Parkes single-dish measurements; they generally appear to coincide with OH maser positions which, in some cases, have been measured to greater precision (Forster & Caswell 1989) than have our methanol positions. Peak intensities and references are also given.

The spectra of the sources, with the exception of 0.65 − 0.05 (Whiteoak et al. 1988), are shown in Fig. 1. They

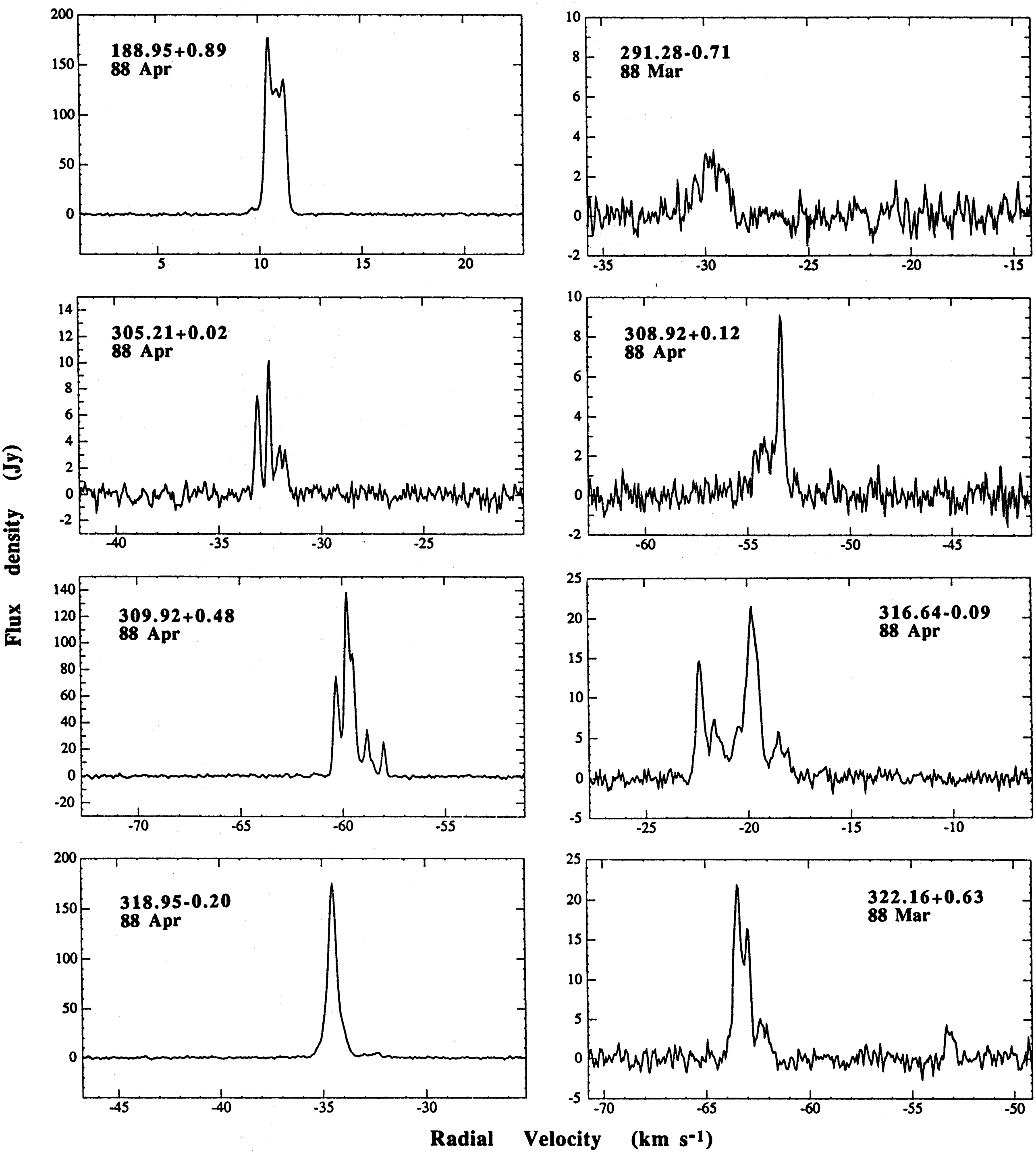

Figure 1. Spectra of 12-GHz methanol masers. All spectra have been Hanning-smoothed to a velocity resolution of 0.1 km s^{-1}. The date of observation (1988 March, 1988 April or 1989 November) is shown. Where there is pronounced variability, spectra at two epochs are shown superposed, sometimes with the third epoch shown separately. For the source 12m351.44 + 0.66, the spectrum as observed with our 2-arcmin beam is shown together with a 'corrected' spectrum in which we have subtracted the confusing effect of the strong nearby source at the edge of the beam.

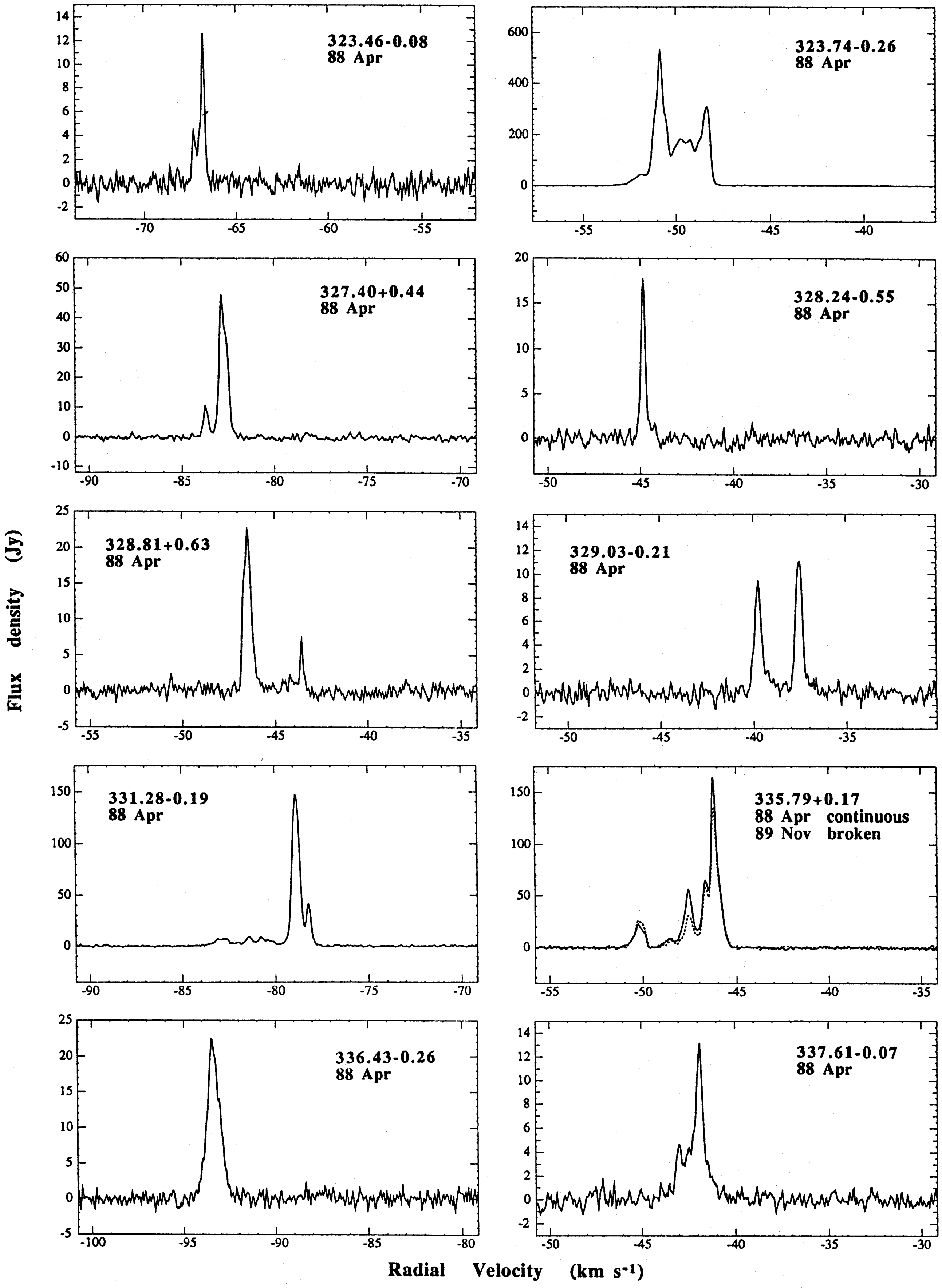

Figure 1 – *continued*

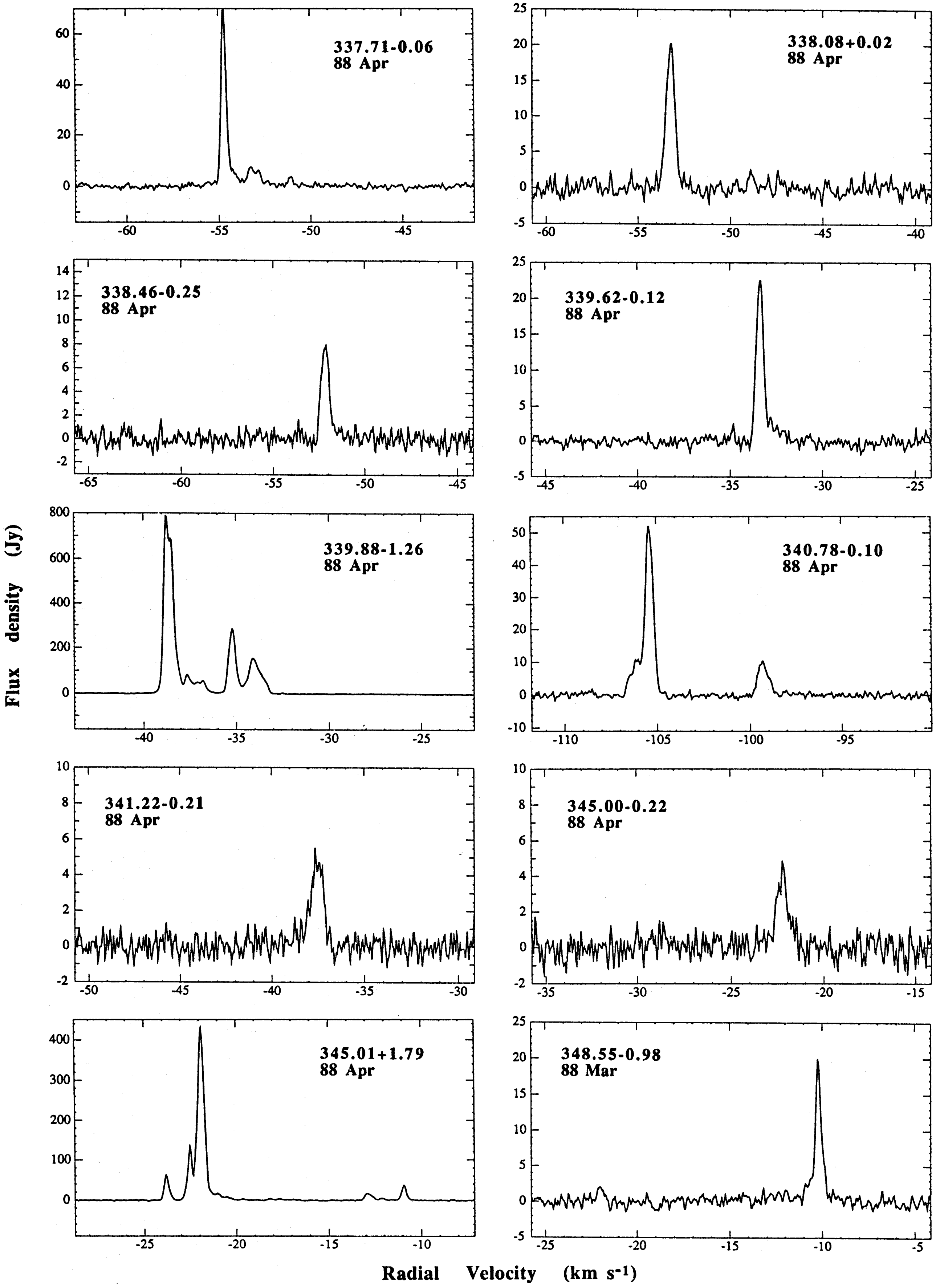

Figure 1 – *continued*

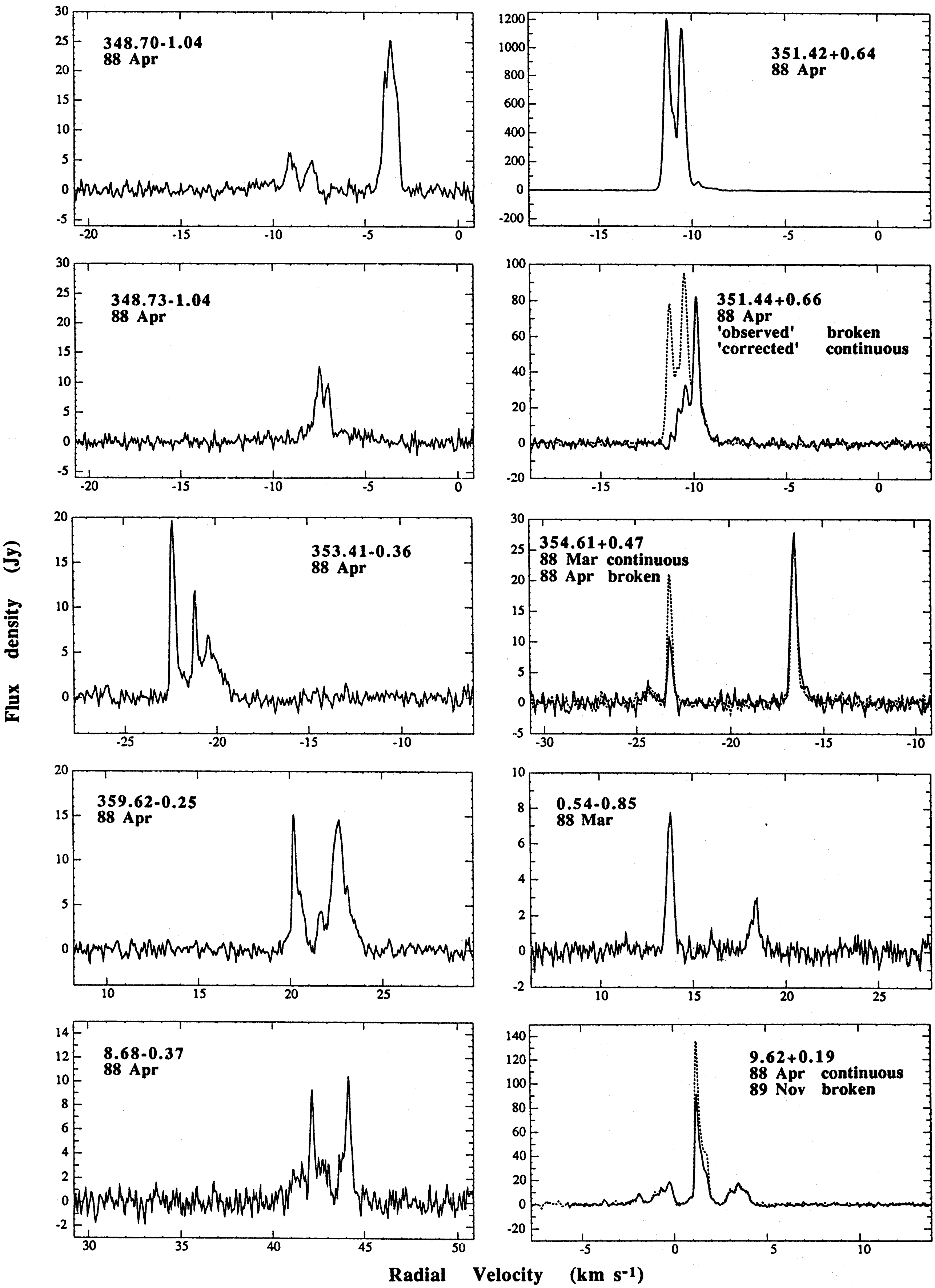

Figure 1 – *continued*

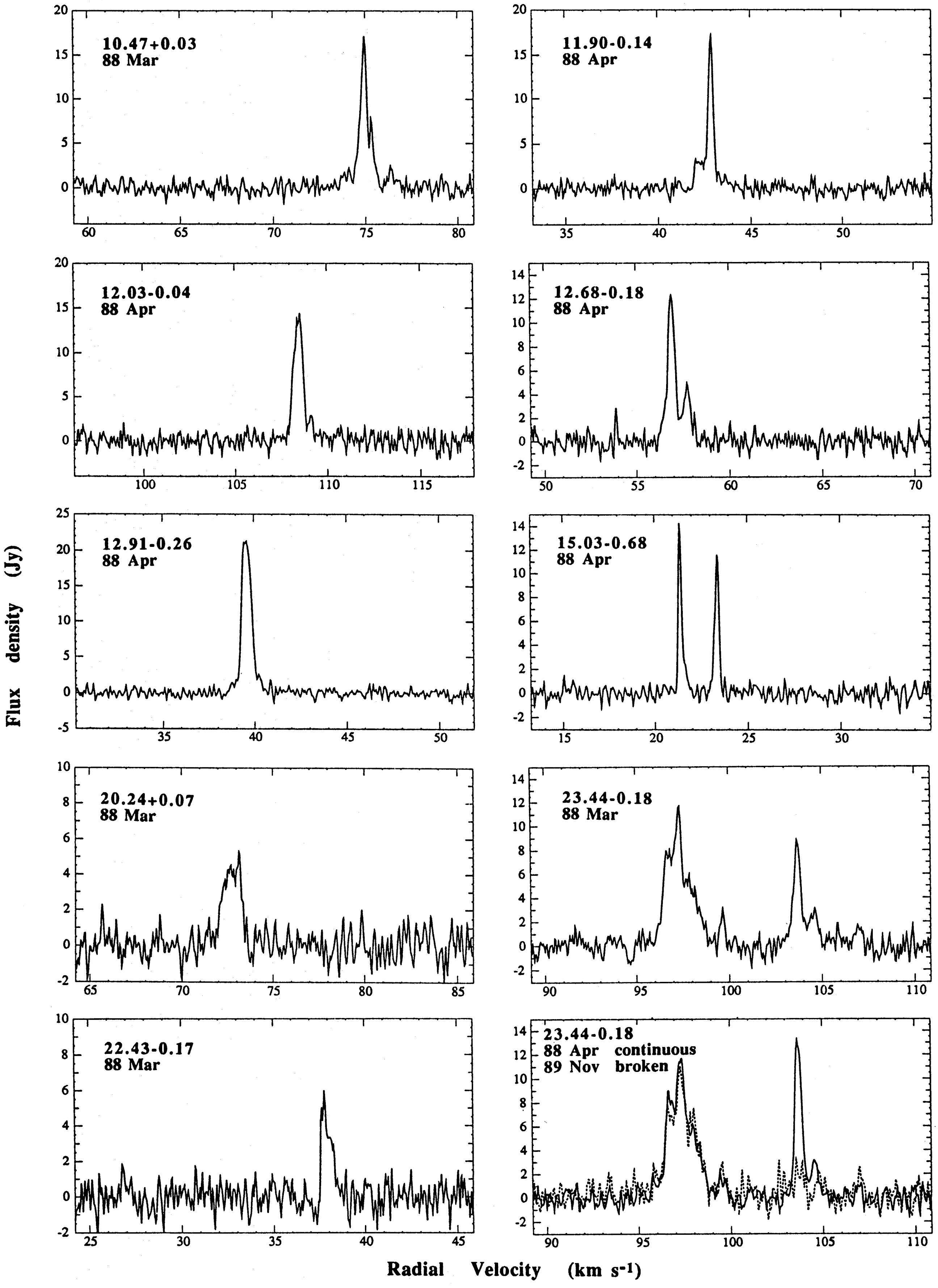

Figure 1 – *continued*

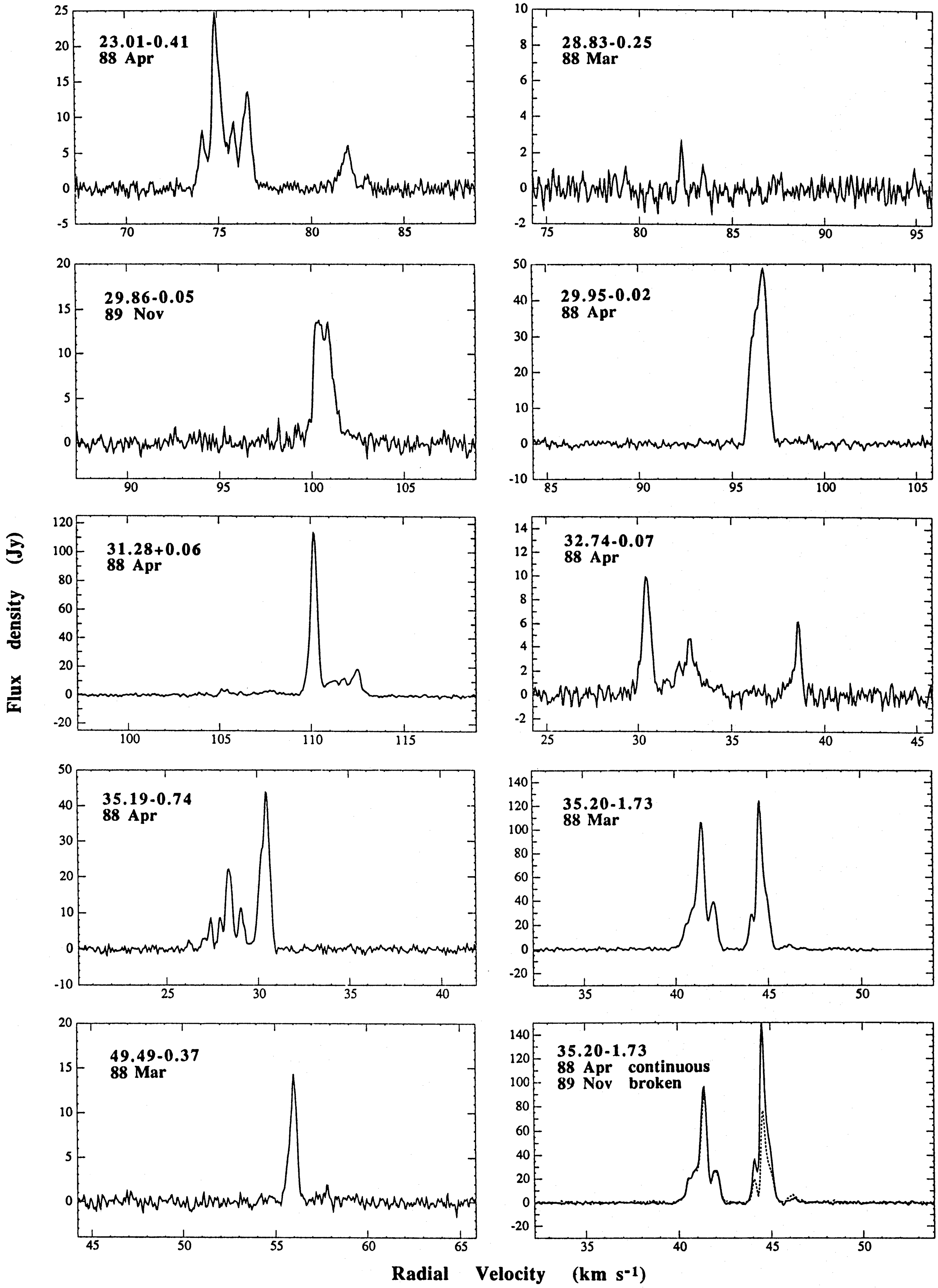

Figure 1 – *continued*

are ordered by increasing galactic longitude, with minor variations to allow repeated observations of the same source to be displayed adjacent to each other.

4 DISCUSSION

In the following discussion, methanol sources are referred to by their galactic coordinates with no prefix if there is no ambiguity. In some situations a shorthand prefix notation is valuable, and we use '12m' to denote 12-GHz methanol masers.

4.1 Source positions

Throughout this paper, equatorial coordinates refer to equinox 1950. The rms errors in our absolute positions are ~ 10 arcsec in each coordinate, caused by telescope pointing errors. However, for different velocity features in a spectrum observed on a five-point grid, relative positions as small as several arcsec are measurable. Thus for most sources we are confident that all of the stronger features (greater than about 10 Jy) lie within a 10-arcsec radius of the mean position, with the following notable exceptions. Features with separation ~ 20 arcsec occur in the sources 329.03 − 0.21 and 345.01 + 1.79. In two other instances, features are separated by more than 1 arcmin, and we list each component as a separate source: 348.70 − 1.04 with 348.73 − 1.04 and 351.42 + 0.64 with 351.44 + 0.66.

4.2 Individual sources of special interest

291.28 − 0.71. The methanol maser was found at the position of an H_2O maser with similar velocity, near − 30 km s^{-1}. The H_2O is remarkable in displaying additional emission at high velocity ($v = -126$ km s^{-1}) which is a factor of 6 stronger than at − 30 km s^{-1} (Caswell et al. 1989), but there is no high-velocity methanol emission. At the position and velocity of the methanol maser, there is no detectable OH maser but there is strong OH absorption that could readily mask any weak emission. The methanol maser is clearly variable (more intense in the 1987 April observation by Norris et al. 1987).

329.03 − 0.21. We have quoted the mean position of the two features visible in the spectrum. They are separated by ~ 20 arcsec, with the stronger one ($v = -37.5$ km s^{-1}) to the south and at later RA.

335.79 + 0.17. There are clear changes in intensity, as can be seen from the spectra of 1988 April and 1989 November (Fig. 1). The feature at velocity − 47.5 km s^{-1} shows the most obvious change, with a reduction by more than 40 per cent, while the feature near − 50 km s^{-1} is either the same or slightly stronger.

336.43 − 0.26. This maser was discovered during a methanol absorption survey (Peng & Whiteoak 1992a) towards an H II region with no reported OH maser. Strong OH absorption at this position may mask any weak OH maser.

341.22 − 0.21. Note that the velocity of the feature now seen is − 37 km s^{-1}, whereas the feature reported by Norris et al. (1987) was at − 46 km s^{-1}. The source is clearly variable on a 1-yr time-scale, with the disappearance of one feature and the strengthening of another.

345.01 + 1.79. There are two centres of activity separated by 20 arcsec. The position quoted is for the strong features between velocities − 20 and − 24 km s^{-1}; this coincides with on OH maser (Forster & Caswell 1989). The features at velocities − 11 and − 13 km s^{-1} are offset to smaller RA and to the north, an offset that has been confirmed by interferometer measurements (Norris et al. 1988) and which is in the direction of an H_2O maser site (Forster & Caswell 1989).

348.70 − 1.04 and 348.73 − 1.04. These sources are separated by 1.5 arcmin; comparison with the Forster & Caswell (1989) OH and H_2O positions shows that 12m 348.70 − 1.04 coincides with an OH maser and 12m 348.73 − 1.04 with an H_2O maser.

351.42 + 0.64 and 351.44 + 0.66. These lie within the H II complex NGC 6334A or 6334N (north). The chief site of OH and H_2O maser emission is at RA $17^h17^m32\overset{s}{.}33$, Dec. $-35°44'02''$ with rms uncertainty ~ 1 arcsec (as reported by Forster & Caswell 1989), and coincides with radio continuum H II region 'F'. [Note that Rodríguez, Cantó & Moran (1982) give an OH position 23 arcsec south of this with claimed errors of 1 arcsec, but there was no evidence of emission from this position in the Forster & Caswell VLA data.] We conclude that the stronger methanol maser is located at radio continuum peak 'F' along with the principal OH and H_2O masers. The second methanol maser is from a site nearly 2 arcmin to the north, but still within the NGC 6334 complex. This weaker methanol maser is confused by the stronger one in single-dish spectra. After ascertaining the two positions, we derived a spectrum for 12m 351.44 + 0.66 from which we have removed the contamination from the stronger source, and this is shown in Fig. 1.

354.61 + 0.47. The two features seen in the spectra arise from the same location to within 20 arcsec, and it can be seen from the spectra in 1988 March and April that the intensity of the feature at velocity − 23 km s^{-1} increased from 10 to 20 Jy in less than 5 weeks. By 1989 November the variable feature had decayed to an intermediate value of 17 Jy.

0.54 − 0.85. The feature at velocity + 13.8 km s^{-1}, with intensity ~ 8 Jy in 1988 March and April, had decreased to ~ 3 Jy in 1989 November.

0.65 − 0.05. In our first report of this source in Sgr B2 (Whiteoak et al. 1988) the position was uncertain, and we now quote a revised position. There is no spectrum shown in Fig. 1.

8.68 − 0.37. Forster & Caswell (1989) list an OH maser at RA $18^h03^m18\overset{s}{.}8$, Dec. $-21°37'53''$; their unpublished data show a second maser at RA $18^h03^m23\overset{s}{.}2$, Dec. $-21°37'31''$. We suggest that the methanol maser coincides with this second OH maser. Caswell et al. (1983) remark that there also appear to be two H_2O maser sites in the vicinity.

9.62 + 0.19. As can be seen from spectra in 1988 April and 1989 November, the strongest feature had increased from 90 to 136 Jy, a variation of at least 50 per cent over 19 months, while the other features show negligible change.

10.47 + 0.03. This was originally listed by Koo et al. (1988) as having an H_2O counterpart but no OH counterpart; however, a corresponding OH maser was reported by Braz & Sivagnanam (1987).

23.44 − 0.18. This is one of the most dramatically variable sources. Through the three epochs 1988 March, 1988 April and 1989 November, the broad feature near velocity

+97 km s^{-1} remained unchanged; the narrow feature at velocity +104 km s^{-1} increased within a month from 8 to 14 Jy and subsequently dropped to less than 2 Jy.

29.86−0.05. This maser was discovered in 1989 November at the site of a previously unreported OH maser (Caswell, unpublished).

29.95−0.02. This methanol maser was discovered by Koo et al. (1988) at the site of an H_2O maser with no detected OH maser.

35.20−1.73. Both features are at the same position (separation less than 15 arcsec). The feature at velocity +44.5 km s^{-1} showed a rapid increase between 1988 March and April and then decayed markedly by 1989 November.

49.49−0.37. This maser within the W51 H II complex is clearly displaced from the well-known OH and H_2O masers; the discovery observations of Batrla et al. (1987) gave the first indication of this, and our refined position, accurate to 10 arcsec, suggests that the methanol maser coincides with a compact radio H II region with flux density 12 Jy at 5 GHz, and designated component 'd' by Scott (1978). The radio continuum source has an IR counterpart, IRS2, and the region has also been studied by Mader, Johnston & Moran (1978).

4.3 Linewidths

In some instances we measure linewidths to half-intensity as narrow as 0.2 km s^{-1}, with some examples occurring in 305.21+0.02, 323.46−0.08, 353.41−0.36 and 15.03−0.68. Many more are present with widths ~0.3 km s^{-1}, as can be seen from the spectra displayed in Fig. 1. Yet broader features include blends of intrinsically narrow features, as is clear from our interferometer measurements (McCutcheon et al. 1988; Norris et al. 1988). For sources observed at several resolutions we find that, with 0.1 km s^{-1} (4 kHz) resolution, even the narrow features show very little decrease in amplitude (a few per cent) relative to measurements with resolution 0.05 km s^{-1}; at 0.2 km s^{-1} resolution, however, the amplitude sometimes drops by as much as 40 per cent.

4.4 Linear polarization

In the present study, most of the sources were observed at only two orthogonal position angles, and so any linear polarization at 45° to these position angles will not be noticeable. However, for the strong sources in Table 1 (with peak intensities exceeding 100 Jy in 1988 March – thus excluding 9.62+0.19) we have measured the linear polarization by taking a set of spectra at four position angles of the feed system (i.e. eight spectra). Our sensitivity limit to polarized flux density is ~5 Jy, and so at the peak of a 100-Jy source we can measure polarization exceeding 5 per cent. Of the 11 sources measured we find polarization between 5 and 10 per cent in the following: 351.42+0.64 (9 per cent for the $v=-10.6$ km s^{-1} feature); 339.88−1.26 (8 per cent at the peak); 323.74−0.26 (8 per cent for the broad feature, not detected for the strongest feature); and 309.92+0.48 (7 per cent). For 351.42+0.64 our measurements provide the first confirmation of the polarization detection reported by Koo et al. (1988). It is now clear that, although no polarization exceeding 10 per cent has been detected and most features are less than 5 per cent polarized, an appreciable fraction of sources, four out of eleven, have some features with polarization between 5 and 10 per cent. From the discussion of maser polarization by Goldreich, Keeley & Kwan (1973), it is expected that the linear polarization is indicative of significant magnetic fields, similar to those implied by linear polarization in water masers; detectable linear polarization in a feature may also indicate that it is saturated. Further, more precise observations of methanol polarization are needed to compare position angles with those of H_2O and OH (on the commonly occurring transitions at both 18 and 5 cm). These may reveal magnetic field orientations.

4.5 Variability

Any assessment of variability must take into account: (i) the intensity calibration uncertainty; (ii) the narrow linewidths (poor frequency resolution reduces the measured peak intensity of narrow lines); (iii) the possibility that features are not all coincident in space (such that relative intensities can exhibit a pronounced dependence on telescope pointing repeatability); and (iv) polarization. Ways of overcoming some of these errors are: absolute calibration – we have concentrated on variability in which one feature is seen to vary relative to another in the same spectrum; resolution – we have chosen the same high-velocity resolution and usually the same centre velocity; position offsets – we have mapped sources with grids to confirm that features coincide to a small fraction of our observing beam; and polarization – this appears, at most, to be ~10 per cent and we use total intensity measurements to avoid error. In view of the need for these many precautions, sensitive valid comparisons are mainly restricted to our present data set. For example, for the strong source 351.42+0.64, the different appearances of our spectrum and the Berkeley spectrum (Koo et al. 1988) are attributable to the proximity of a second source and to the larger beamwidth of the Hat Creek telescope. Despite these potentially misleading sources of error, we are confident that many features show fluctuations of ~10 per cent on a time-scale of a month, and that there is much more pronounced variability in the case of eight sources remarked on in the source notes. The fastest increase is by a factor of 2 in 1 month (354.61+0.47); the decreases that we found are somewhat slower, with the fastest being a fall from 14 to 2 Jy in 19 months (23.44−0.18). Narrow velocity features are most commonly variable. A rapid rise and slow decay may be a general feature of the variability. On present evidence, the variability activity, as gauged by the prevalence of variable features or by the rapidity and magnitude of the fluctuations, is intermediate between the relatively stable main-line OH and the highly unstable 22-GHz H_2O masers. The presence of marked variability can also be a clue as to the degree of saturation of a maser – it is believed that features showing such variability on a short time-scale are most likely to be unsaturated masers, in which the maser gain is an exponential rather than a linear function of path-length.

4.6 Maser classification

We have loosely referred to all the sources as masers although, strictly, the evidence for this is confined to the stronger sources. As noted by Batrla et al. (1987), in a few instances the inferred brightness temperatures, even with a crude limit of about 1 arcmin on the angular size, are several hundred kelvin while the linewidths correspond to somewhat lower kinetic temperatures. Our interferometer measurements (McCutcheon et al. 1988; Norris et al. 1988) place much tighter constraints on the angular sizes and confirm that, for all of the 10 strong sources observed, the sizes are very small and characteristic of maser excitation. The occurrence of appreciable polarization is also indicative of excitation that is, at the very least, non-thermal, while variability on short time-scales provides further evidence. As noted in Sections 4.4 and 4.5, polarization and variability can provide clues as to the degree of saturation of masers. It is notable that the clearly polarized features are not amongst the ones found to be distinctly variable. In particular, 12m 323.74 − 0.26 has a broad plateau (in velocity) showing linear polarization but no variability, plus a narrower, stronger feature showing variability but no polarization.

4.7 The pumping scheme

Menten (1991a) has summarized the present limited understanding of Class II methanol masers. Preliminary results of an excitation study of 12-GHz masers have also been presented by Peng & Whiteoak (1992b). Promising pumping schemes have been proposed but require more detailed computation and input data such as collision rates that are, as yet, only poorly estimated. In this situation, phenomenological descriptions and correlations are useful in narrowing down the range of likely schemes. High-sensitivity continuum observations are needed to assess whether a high-brightness radio continuum background is needed. The association of 12-GHz masers with OH masers suggests similarity in the required environments and, for both varieties, there has been strong advocacy of infrared (~ 60 μm) radiation pumping. But, equally, the high collision rates in these dense regions are likely to play a significant part.

4.8 Statistics

Restricting ourselves to the search towards the sample of 173 OH masers in star-forming regions, we have found 53 methanol masers, corrresponding to a detection rate of 30 per cent. Clearly this statistic depends on the detection limit and will increase with improved sensitivity. We have remarked in Section 4.2 on individual sources with nearby OH and H_2O masers: a close association with a single OH maser is common amongst most of the methanol masers. We have compared the peak intensity of each methanol maser with that of the nearest associated OH maser and found a large scatter in this intensity ratio, with a range from at least 600 to 1/50. The median ratio, ignoring non-detections, is ~ 5 and this would drop below 1 if methanol non-detections were included. Koo et al. (1988) aimed their methanol search towards the positions of H_2O masers and made a comparison of methanol and H_2O intensities, but the statistics are small (11 detections from 78 search positions) and are dominated by methanol non-detections.

From the searches made to date, it is not certain whether the methanol masers are associated preferentially with the OH or the H_2O masers. It appears that H_2O masers occur at most OH maser sites (Caswell et al. 1989; Forster & Caswell 1989), but there is some indication that H_2O maser emission occurs also at locations not favourable to masering of either OH or methanol. In particular, associated with the intense high-velocity masers H_2O 291.28 − 0.71 ($v = -126$ km s^{-1}) and H_2O 320.25 − 0.31 ($v = -156$ km s^{-1}) listed by Caswell et al. (1989), there are no detectable OH masers and we found no methanol masers. Considering the methanol maser sites where there is an H_2O maser but no OH maser, we find in the case of 291.28 − 0.71 that there is strong OH absorption which may mask any OH maser (Caswell & Haynes 1987) and this may also be true for 29.95 − 0.02. At present the data are consistent with all three maser species being present together at star formation sites, but with a wide range of intensity ratios. There is some prospect that the relative intensities may be indicative of either a specific evolutionary stage or perhaps a limited range of mass for the exciting star, and it will be possible to assess this better when surveys of the strong 6.6-GHz methanol transition are complete. High-resolution mapping will be needed to distinguish the precise zones favourable to each masing species.

5 CONCLUSIONS

The present results represent a comprehensive search for 12-GHz methanol masers in the directions of OH masers readily accessible to the Parkes telescope (south of declination 22°), especially those located along the galactic plane in the longitude range 270° through 360° to 60°. In addition to providing a catalogue of southern methanol 12-GHz masers, we have identified some sources showing significant polarization and others showing marked variability. In future studies, variability will be monitored on a longer time-scale, and detailed comparison will be made with the more recently discovered 6.6-GHz methanol transition.

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