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Variability of Methanol Masers

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Abstract: Sites of recent star formation often radiate strong maser emission from methanol transitions near 6·6 and 12 GHz. We have studied many of these masers over several years and find that intensity variations are common on both transitions. We present observations which demonstrate marked variability in 48 sources. We explore the characteristics of the variability and find it to be typically quasi-periodic, on a timescale of between a month and several years. The amplitude of the variation is most commonly less than a factor of two, but can reach factors of ten. The variability of different features in a source is usually independent. Variability of features seen at both 6·6 and 12 GHz is sometimes correlated, with larger amplitudes usually seen at 12 GHz. A likely inference is that variations are occasionally due to a change in the pump rate throughout the masing region, but most are consistent with a change in the masing path length due to large-scale motions. In addition, it is likely that the majority of 6·6-GHz masers are saturated whereas the 12-GHz masers may be somewhat less saturated.

Keywords: masers — stars: formation — ISM: molecules — radio lines: ISM

1. Introduction

In the vicinity of star-forming regions, several transitions of methanol exhibit strong maser emission. The masers fall into two varieties (Menten 1991a), and here we will be concerned with those of 'class II'. These emit principally from transitions near 6·6 and 12 GHz. They appear to be closely associated with the ultra-compact HII regions around recently formed massive stars, and submillimetre radiation is probably vital to the maser pumping mechanism (Cragg et al. 1992). In earlier papers (Caswell et al. 1993, 1995a; subsequently referred to as C+93 and C+95a) we reported surveys of 12- and 6·6-GHz methanol masers; here we study the variability of these masers over several years.

2. Observations

Full details of our observations are given elsewhere (C+95*a*) and here we briefly summarise them. The masers were observed with the Parkes 64-m telescope in the periods 1992 February 29, March 5–9, June 1–9, September 24–29, December 17–24 and 1993 September 27–30. Dual-channel receivers, accepting two circular polarisations, were used at both 6·6 and 12 GHz. The new Parkes correlator was configured to record a 2048-channel spectrum for each polarisation, spanning 2 MHz at 6·6 GHz and 4 MHz at 12 GHz. The adopted rest frequencies were 6668·518 MHz (Menten 1991b) and 12178·595 MHz (Gaines et al. 1974). The intensity calibration at 6·6 GHz is relative to Hydra A with an assumed peak flux density (with our beamwidth-to-half-power of 3·3 arcmin) of 9·84 Jy. At 12 GHz the calibration is relative to Virgo A with intensity of 33·5 Jy (peak of 31·4 Jy observed with our 2·0-arcmin beamwidth). The calibration error of individual spectra may occasionally be as large as 10% but is usually less than 5%.

3. Results

For the statistics of occurrence of variability in methanol masers, we refer to our recent survey paper (C+95a). The earlier assessment of variability was conservative, and made before the 1993 September dataset was finally calibrated; we can now recognise some additional variable features. For the present study we have selected most of the masers that have shown significantly variable features, that is, those with changes greater than 10% on either the 6·6- or 12-GHz transitions. We have omitted a few sources listed as highly variable in the C+95a compilation, chiefly those with single weak features such as 269·15−1·13 and 311·96+0·14, sources which flared briefly such as 321·71+1·17, or sources observed on only two occasions.

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Our results can best be seen in Figures 1–8 where, for each source, we have superimposed total-intensity spectra for four different epochs. The sources are ordered by Galactic longitude with some variations for convenience of page layout. Note that, as specified in the figure caption, the epochs covered are not precisely the same for the two transitions; in particular, the 6·6-GHz spectra obtained 1992 March are not shown since they were of slightly lower quality, and there are no 12-GHz spectra for 1993 September. At both transitions, the solid-line spectrum shows our most recent measurement. Spectra of 48 sources are shown, all of them at 6·6 GHz and 28 at 12 GHz. A further 7 of the 48 sources have been detected at 12 GHz as mentioned in the individual source notes, but the spectra are of less interest (usually because the source is weak or observed on only one or two occasions) and are not shown. Most of the sources have highly variable features at both 6·6 and 12 GHz but a few are markedly variable in only one transition. (For example, one of the 12-GHz spectra shows no variation, in contrast to the variable 6·6-GHz spectrum; and 13 of the 6·6-GHz spectra show slight or no variation, in contrast to the more variable 12-GHz spectra.)

The figures give a good measure of which features are highly variable and which are essentially stable. However, it is not easy to see the detailed history of the variations, so we have also summarised the variability in Table 1; this tabulation includes intensities at several epochs which are not plotted in the present set of figures, with some 12-GHz values taken from C+93 and a few 6·6-GHz values from Menten (1991b), as described for individual sources in Section 4.

Table 1 lists all the sources with their Galactic coordinates (subsequently used as source names) and equatorial coordinates. We have selected at least one feature from each spectrum and listed its flux density variation with time. The selected features are usually the most highly variable. However, in a few cases a listed feature is only slightly variable, but matches a highly variable feature on the other transition. Where we have selected two features from a spectrum, they often show variability that is clearly not synchronised. In total, 97 features are tabulated. We have also assessed the magnitude of the variability and its timescale as discussed in Section 5a; these quantities are characterised as the ratio of maximum-to-minimum flux density, and the interval from minimum to maximum (adopting the convention, positive for flux density increases with increasing time, and negative for decreases). Both parameters are listed in Table 1.

In the notes on individual sources in the following section, we remark on the type of variation (monotonic change; flare and decay; decay and recovery; quasi-periodic), and whether the variations are synchronised for different features and for the two transitions.

4. Individual Sources

192·60–0·05. Three major features have varied by 10% in 18 months, with some increasing while others decreased. Note the new feature of 1993 September, 2·8 Jy at velocity +1·8 km s^{-1}, which was less than 0·25 Jy in 1992 December and thus increased by a factor of more than 10 in 9 months.

213·71–12·60. The feature at velocity +10·5 km s^{-1} decreased in amplitude by a factor of 3 from 1992 June to 1993 September. Our spectra show other features variable, but by smaller amounts. Menten (1991b) measured a peak intensity of 160 Jy in 1991 June, about half our value, which shows that the strongest feature increased by a factor of 2 in 9 months but has subsequently decreased. At 12 GHz (spectra not shown), the weaker features have varied by 30% but we have not detected a counterpart to the most variable 6·6-GHz feature.

290·37+1·66. The three major features show variability with the same pattern: a maximum in 1992 June and minimum in 1993 September. The strongest component dropped to half intensity and the weakest to one-tenth in the 15-month interval.

291·28–0·71. The maser is extremely variable on the 12-GHz methanol transition (C+93). Most notably, no feature exceeded 3 Jy in 1989 November, compared to a peak of 25 Jy in 1992 March, thus showing an increase by a factor of 8 in 2·5 years. The spectra show that variations have continued at 12 and 6·6 GHz. The tabulated feature at velocity −29·7 km s^{-1}, present at both 6·6 and 12 GHz, is in a complex region of the spectrum, so the apparent asynchronism of the variability in the two transitions may not be significant.

294·52–1·62. Several features have remained constant, while others have changed by more than a factor of 2, with some increasing and some decreasing.

309·92+0·48. Many features are seen with a high signal-to-noise ratio and are clearly varying to different extents. Since the variations are small (mostly less than 10%), the uncertainty in our absolute scaling makes it difficult to see which ones are most variable. For this source we investigated the effect of applying scaling factors (changes of less than 10%) to the original data to bring the brightest peak and several other peaks to the same value. Other features were then seen to be variable at nearly the 10% level. At 12 GHz, our data extend back to 1988. A 4% gain change was applied for one epoch which removed variability for one feature but other features still vary by up to 20%.

311·64–0·38. The intensity of both major features was high in 1992 June, decayed simultaneously in 1992 September and 1992 December by approximately 40%, and recovered in 1993 September.

312·60+0·04. The feature at velocity $-67\cdot9$ km s^{-1} varied by a factor of 2 but there was little change in the other two features.

316·64–0·09. The strongest feature shows a minimum intensity at both 6·6 and 12 GHz in 1992 September and December. At 12 GHz the 1988 peak of the strongest feature was 22 Jy, intermediate between the extremes of 1992. Also note that the feature at velocity $-22\cdot2$ km s^{-1} has been stable at 14 Jy in both the present data and in 1988.

316·81–0·06. Many features are strongly variable at 6·6 GHz. At 12 GHz most features are stable, but one, at velocity -42 km s^{-1}, has decayed dramatically and also decreased at 6·6 GHz in the same period.

318·05+0·08. Variability is quite pronounced, exceeding a factor of 2 in several features. The two features tabulated do not vary synchronously, with one showing an almost monotonic decrease and the other a subsequent rise after an initial fall.

320·23–0·29 shows clear variability with some features stable, some increasing and some decreasing.

322·16+0·64 is variable at both 6·6 and 12 GHz. At 12 GHz, the main feature weakened from 22 Jy (1988 March) to a minimum of 12·5 Jy (1992 June).

327·29–0·58. At 6·6 GHz there is a feature at velocity -37 km s^{-1} which is stable at 2·3 Jy, but several other features, between -47 and -49 km s^{-1}, are highly variable. Over the corresponding velocity range of the variable features, weak 12-GHz emission is present and is also highly variable, and is perhaps synchronised with the 6·6-GHz variations.

331·13–0·24 is extremely variable, with some features falling to a minimum and recovering (velocities -84 to -87 km s^{-1}) while others (-90 to -92 km s^{-1}) increased and then decayed.

331·28–0·19. At 6·6 GHz, many features show little variation but two features, at velocities $-80\cdot8$ and $-80\cdot4$ km s^{-1}, have decreased between 1992 June and 1993 September. At 12 GHz, changes in most features are small, less than 10%, even on the larger timescale 1988 April to 1992 June; however, some have increased while others have decreased and thus they represent real variations rather than possible gain calibration errors.

331·34–0·35. Several features are highly variable, some increasing and others decreasing, as can be seen from the two examples in Table 1.

332·72–0·62. The feature at velocity $-45\cdot5$ km s^{-1} is highly variable, while other features are much less so.

335·79+0·17. Many features are present, with the two most variable at 6·6 GHz both monotonically decreasing in our observing period. At 12 GHz, the feature at velocity $-47\cdot5$ km s^{-1} is variable, decreasing within the 1988–89 period (C+93), increasing from 1992 March to 1992 September and then decreasing.

336·99–0·03. The strong peak at velocity $-125\cdot8$ km s^{-1} is highly variable and many weak features, although not prominent, show large percentage changes of intensity, both increases and decreases.

337·92–0·46. Of the two strongest features, one has increased and the other decreased. At 12 GHz there is only a weak feature, at velocity $-37\cdot9$ km s^{-1}.

338·46–0·25. At 6·6 GHz, four features show significant changes. At 12 GHz there is a single feature at velocity $-52\cdot1$ km s^{-1}, which was 8 Jy in both 1988 April and 1992 March, but increased to 10 Jy in 1992 December.

339·62–0·12. The masers are variable at both 6·6 and 12 GHz. Changes are mostly small but, at 12 GHz, a feature at $-36\cdot4$ km s^{-1} is highly variable.

340·79–0·10. At both 6·6 and 12 GHz, some features are stable while others vary by up to factors of two or more. At 12 GHz, the 1988 intensities (C+93) generally lie within the range of the 1992 intensities.

341·22–0·21 has a wide velocity spread with two clearly defined ranges. The source is variable in many features at 6·6 GHz by up to 30%. It is even more variable at 12 GHz, with all features briefly reaching their 1988 intensities, but generally lying below those values, by as much as a factor of 3.

345·00–0·22 is variable in many features but three have been stable; note that we have no

6·6-GHz measurement in 1993 September. Menten (1991b) reported a peak of 148 Jy in 1991 June which we now find has increased to a maximum of 448 Jy in 1992 June. At 12 GHz also, this feature flared to a maximum in 1992 June, reaching 20·3 Jy, compared to a value of 5 Jy in 1988 April.

345·50+0·35. The 6·6-GHz methanol spectra display at least 10 peaks, with most showing some

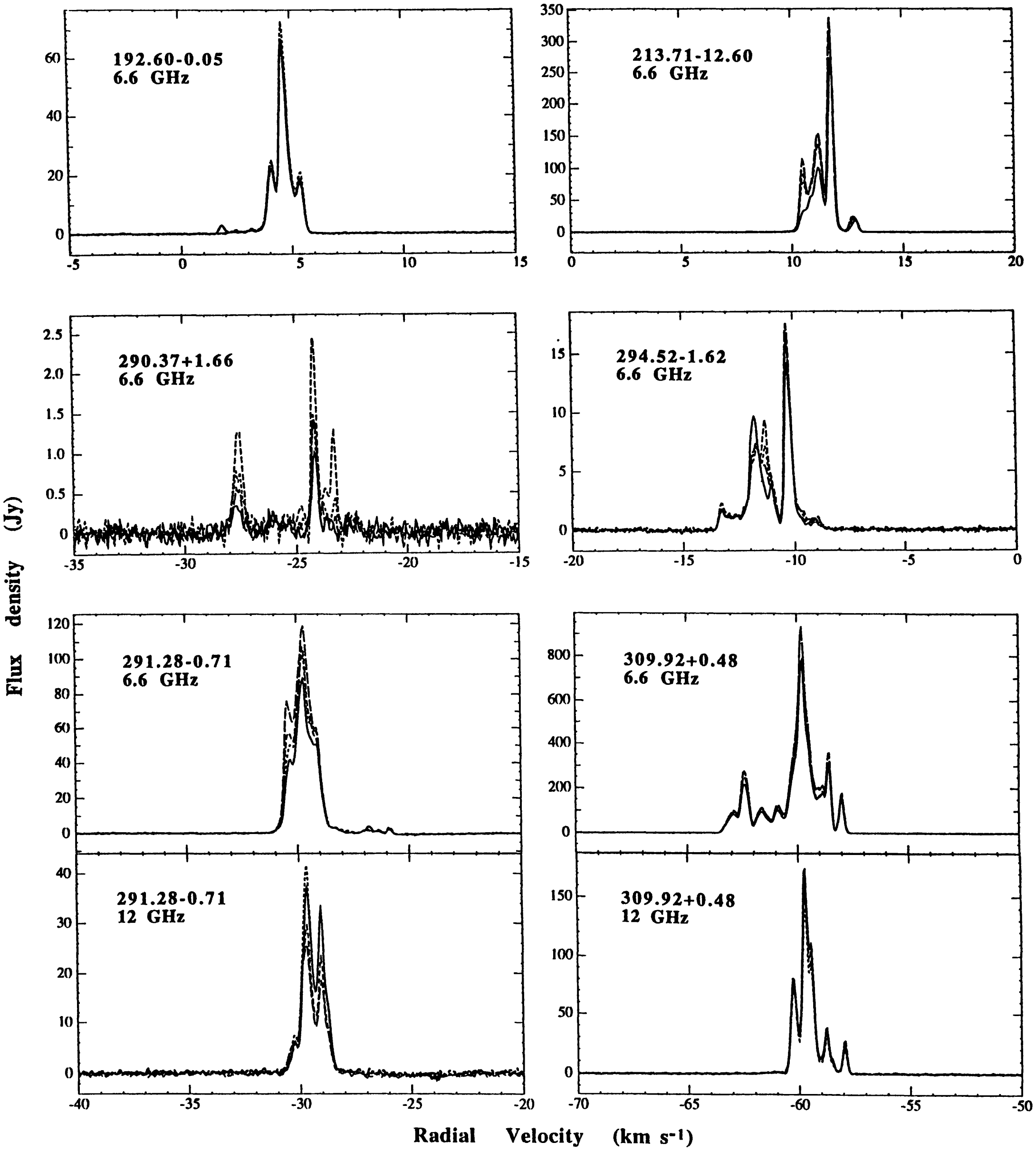

Figure 1—Spectra of 6·6- and 12-GHz methanol masers. All spectra have been Hanning smoothed to a velocity resolution of 0·1 km s^{-1}. Spectra at different epochs are shown with a continuous line for the most recent epoch and a variety of broken lines for earlier epochs. The 6·6-GHz spectra were obtained in 1992 June, September, December, and 1993 September. The 12-GHz spectra were obtained in 1992 March, June, September and December

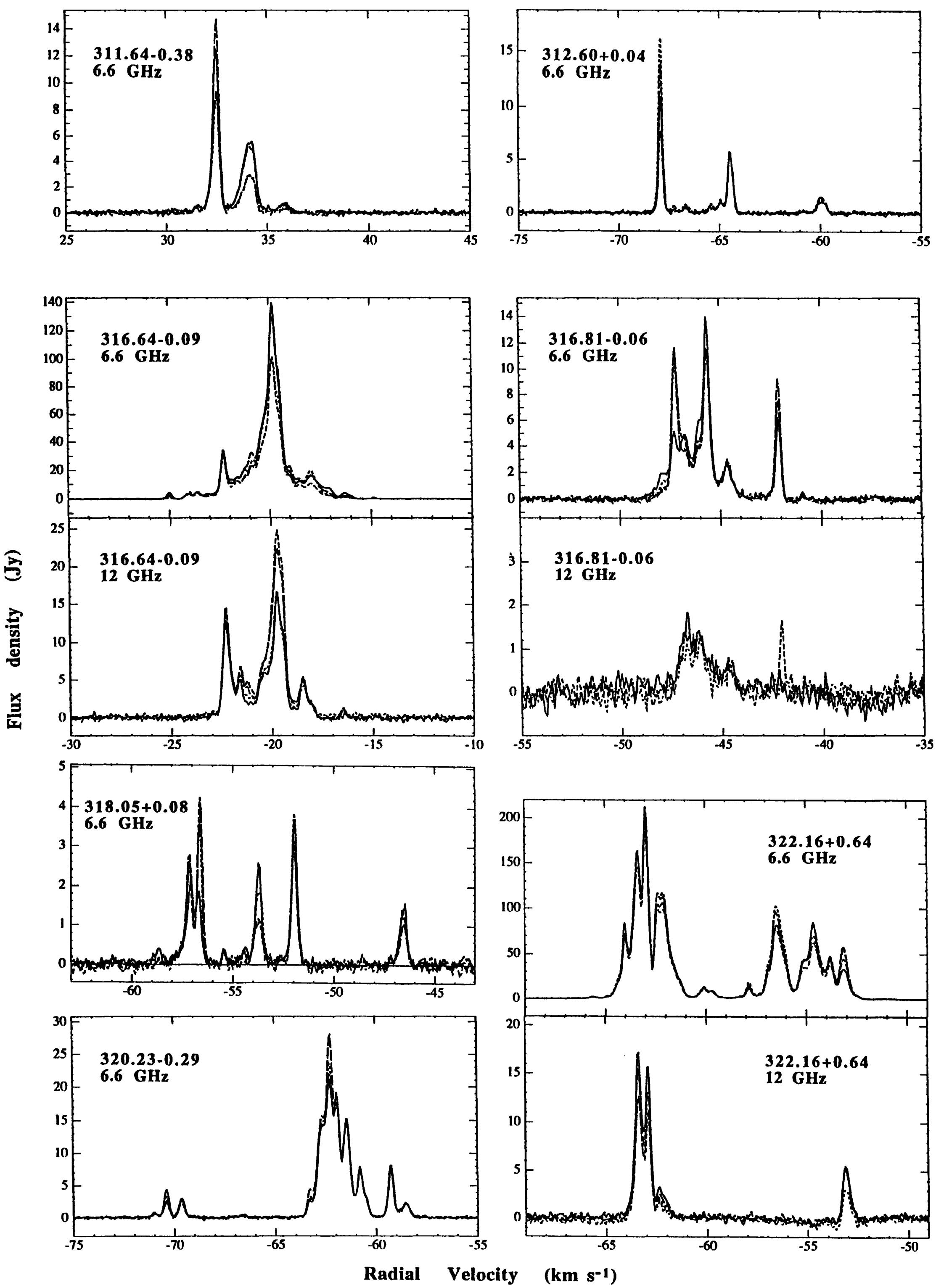

Figure 2—Spectra of 6·6- and 12-GHz methanol masers; details as for Figure 1.

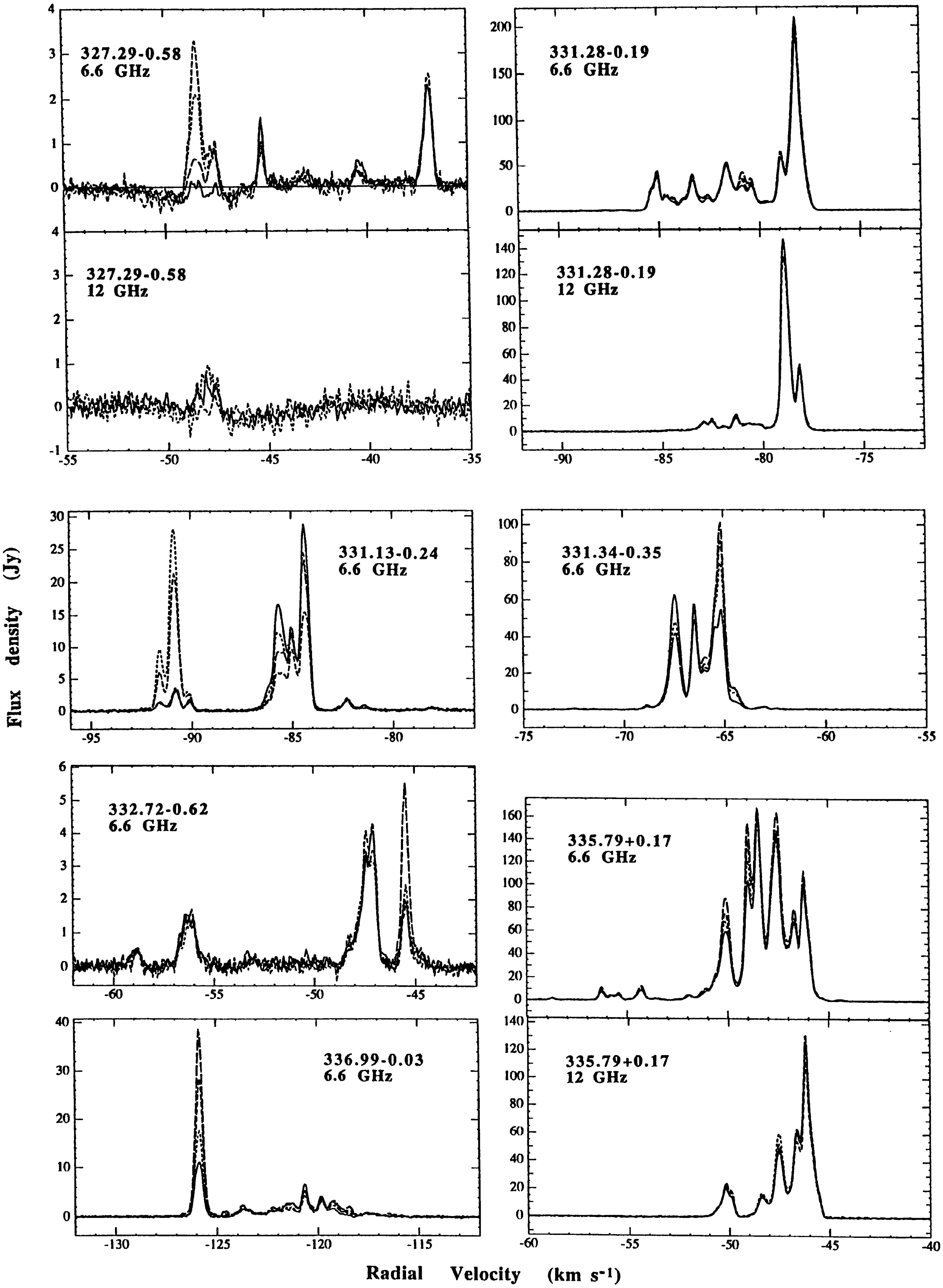

Figure 3—Spectra of 6·6- and 12-GHz methanol masers; details as for Figure 1.

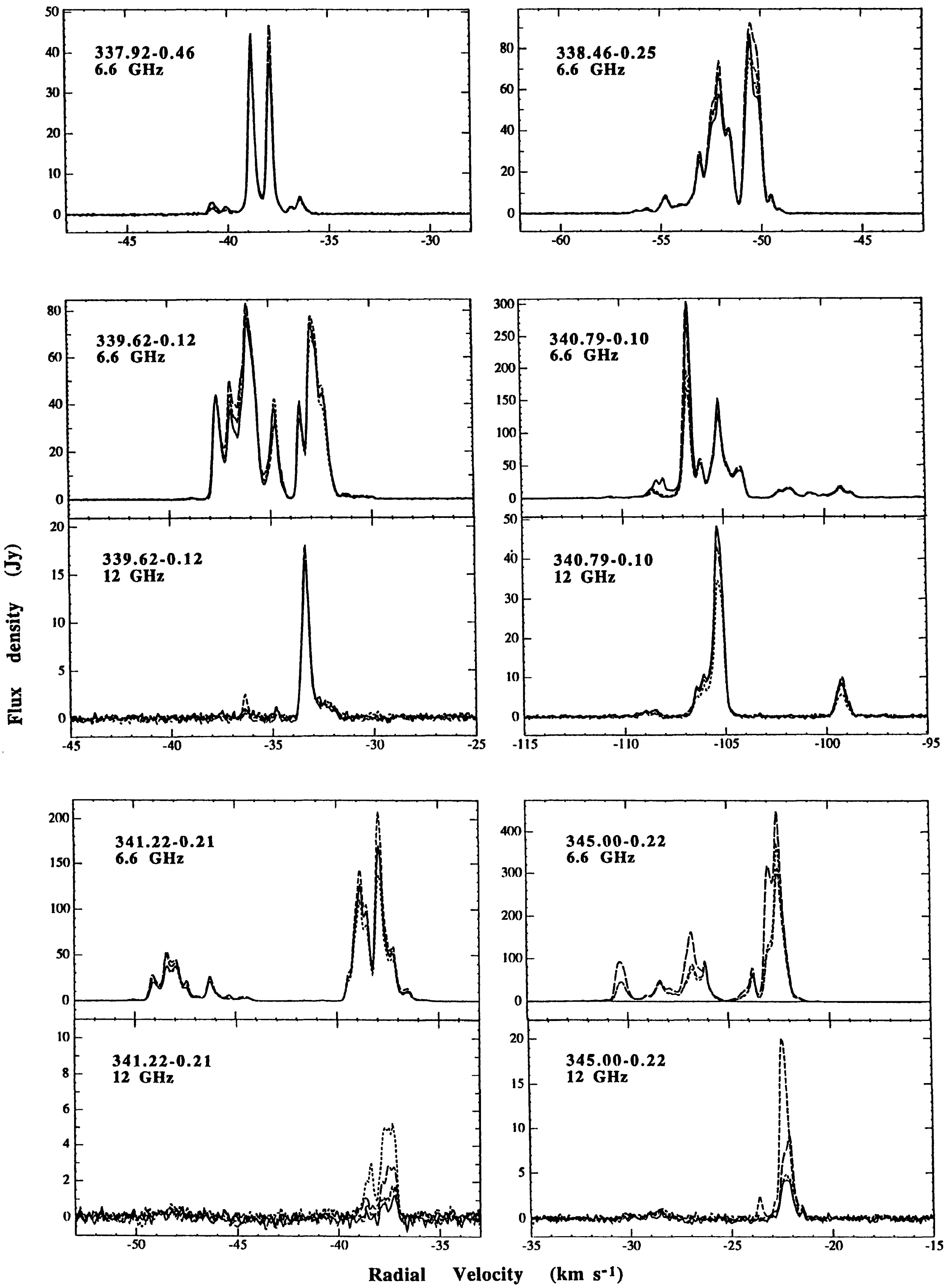

Figure 4—Spectra of 6·6- and 12-GHz methanol masers; details as for Figure 1.

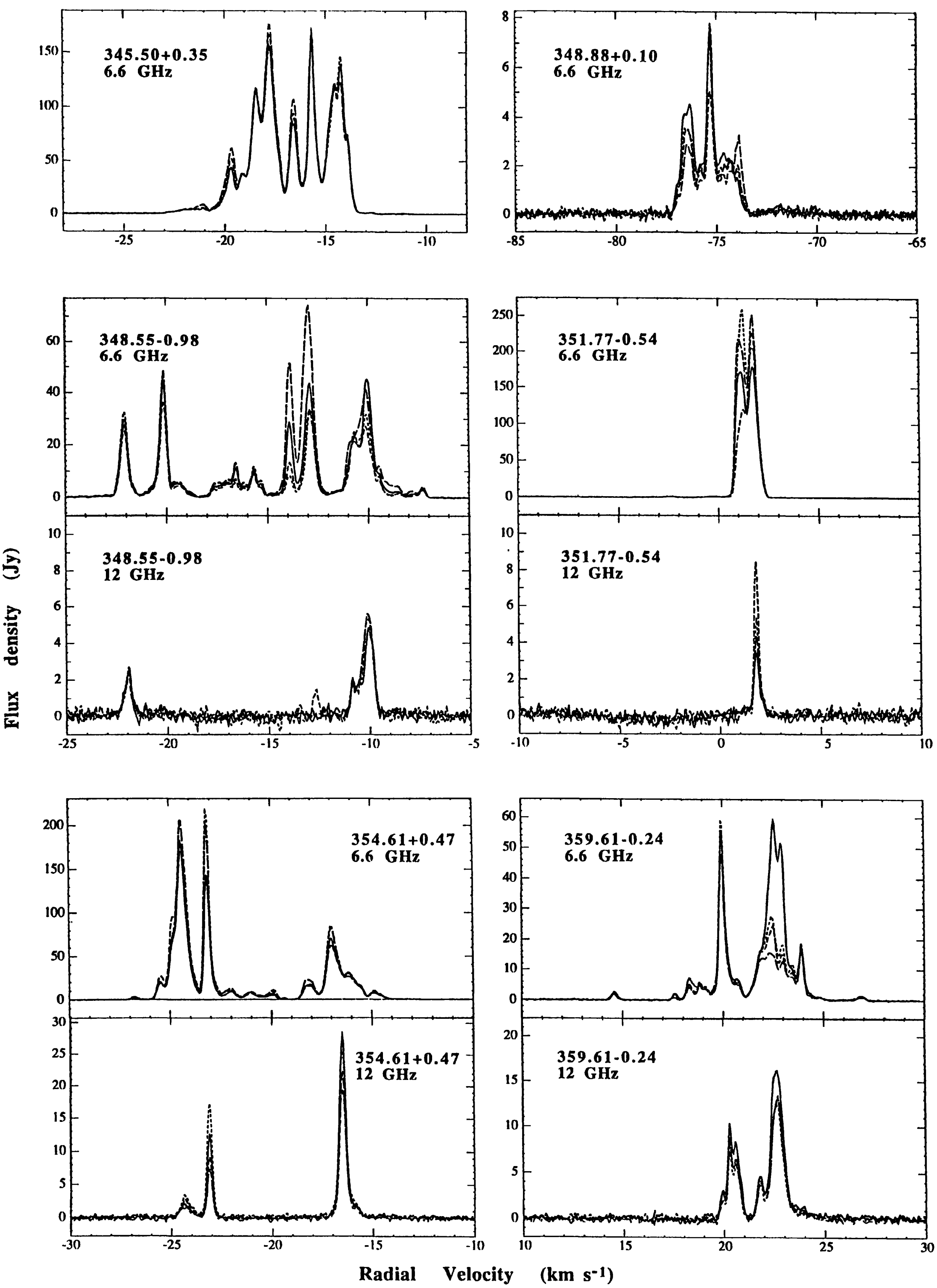

Figure 5—Spectra of 6·6- and 12-GHz methanol masers; details as for Figure 1.

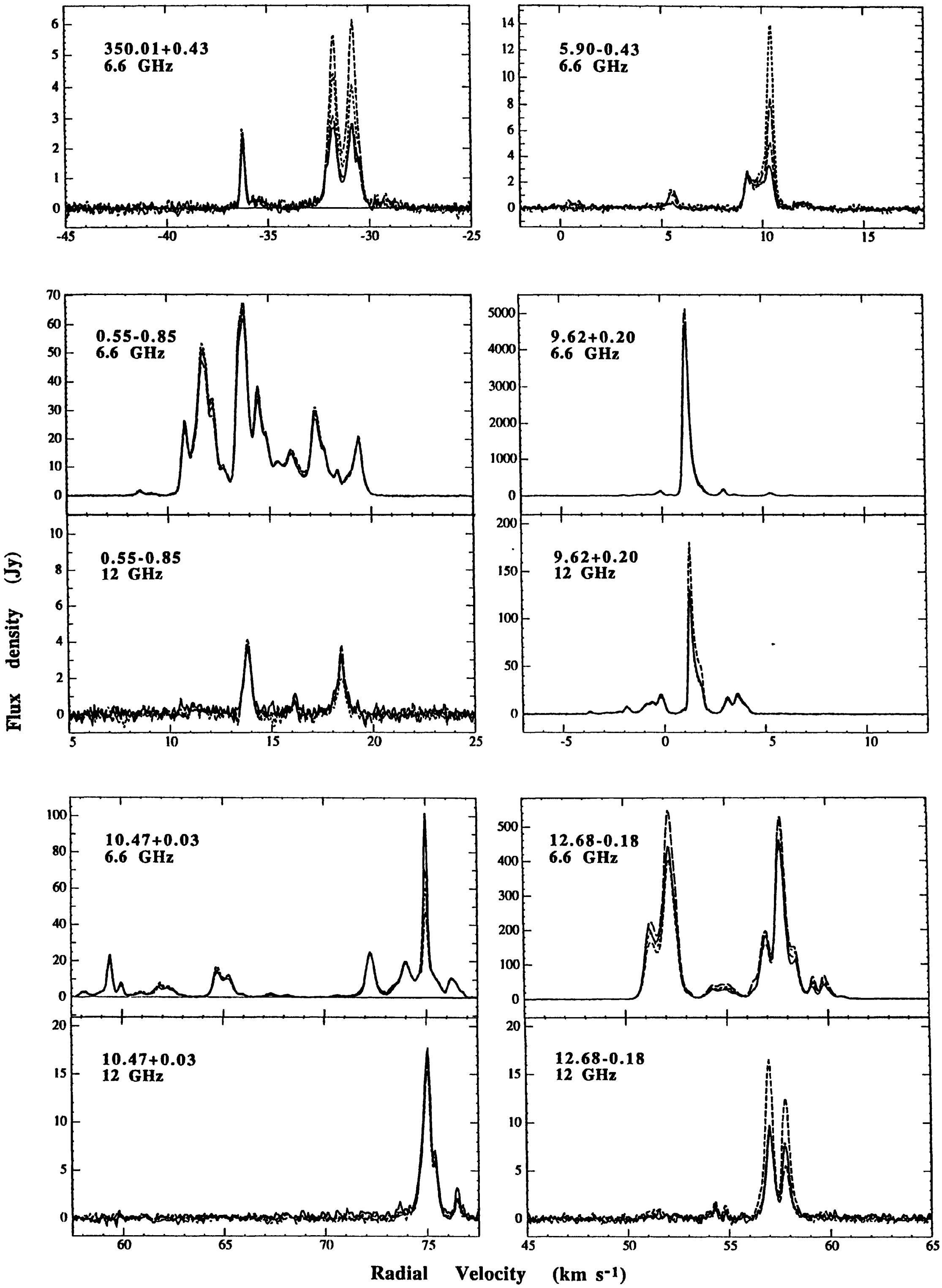

Figure 6—Spectra of 6·6- and 12-GHz methanol masers; details as for Figure 1.

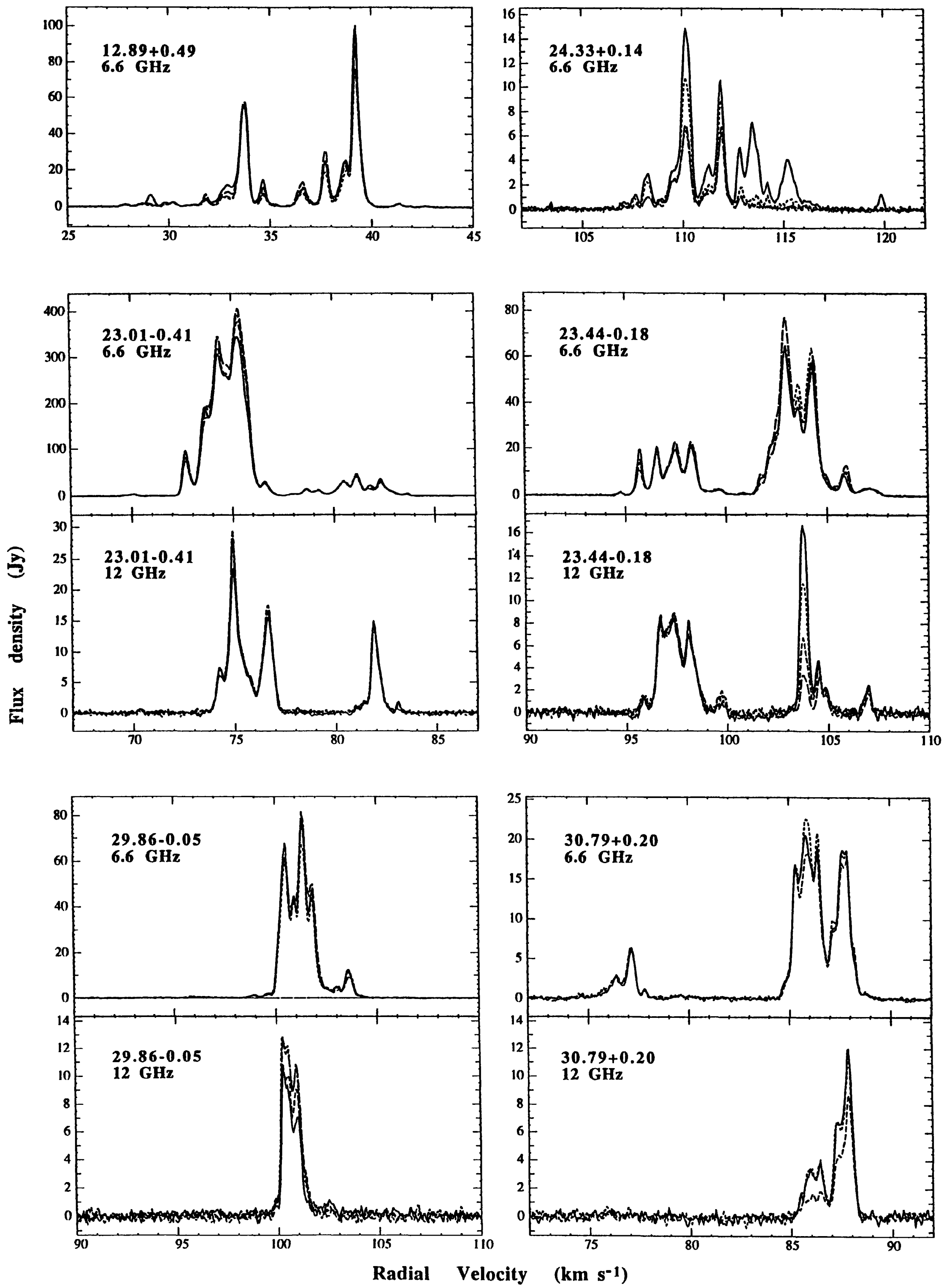

Figure 7—Spectra of 6·6- and 12-GHz methanol masers; details as for Figure 1.

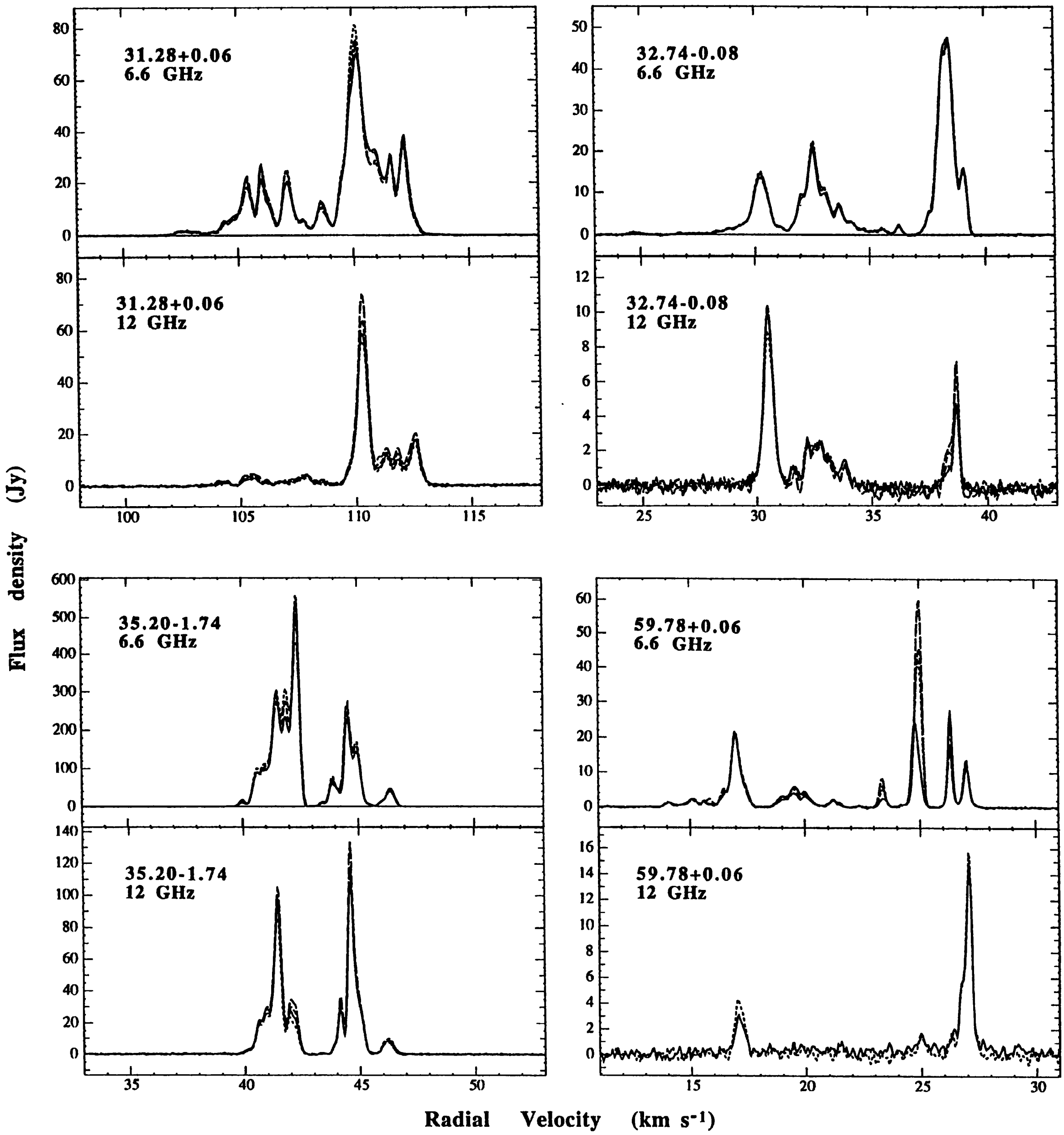

Figure 8—Spectra of 6·6- and 12-GHz methanol masers; details as for Figure 1.

variability. The peak intensity is similar to the value of 171 Jy measured by Menten (1991b) in 1991 June. We tabulate the intensities of the most variable feature at $-19\cdot7$ km s^{-1} which flared to a maximum in 1992 June; note that the adjacent features at velocities $-19\cdot1$ and $-18\cdot5$ km s^{-1} show no variability. The spectrum of the 12-GHz methanol transition was observed only in 1992 September and December and shows no large variation.

348·55−0·98 is exceptionally variable at 6·6 GHz. It is also interesting because it possesses two centres separated by 2 arcsec. It seems as if the northern centre of activity (velocities −22 and −20 km s^{-1}) shows little variability, but many of the southern features (velocities −10 to −13 km s^{-1}) vary greatly. The most variable is at velocity $-13\cdot9$ km s^{-1} (this has no 12-GHz counterpart). At 12 GHz the velocity −22 km s^{-1} feature of

Table 1. Methanol masers. Selected variable features on the 6·6-GHz and 12-GHz transitions

Methanol maser (l,b)	RA (1950) (h m s)	Dec (1950) (° ′ ″)	Trans Freq (GHz)	Velocity (km s^{-1})	Peak 88-91 (Jy)	Flux density at different epochs* 92m (Jy)	92j (Jy)	92s (Jy)	92d (Jy)	93s (Jy)	Max/min intensity (ratio)	Time scale (month)
192.60–0.05	06 09 59.1	+18 00 10	6.6	+1.8		<0.25	<0.25	<0.25	<0.25	2.8	>11.2	+9
213.71–12.60	06 05 21.7	–06 22 28	6.6	+10.5		95	112	90	78	34	3.29	-15
290.37+1.66	11 10 07.7	–58 29 59	6.6	-24.2		1.3	1.4	2.4	1.5	1.0	2.40	-12
291.28–0.71	11 09 46.7	–61 02 06	6.6	-29.7		110	119	107	103	88	1.35	-15
291.28–0.71	11 09 46.7	–61 02 06	12	-29.7	<3	25.0	29.0	41.5	37.0		>13.8	+34
294.52–1.62	11 33 15.0	–62 58 13	6.6	-11.3		9.0	5.5	9.3	7.0	3.1	1.69	±3
309.92+0.48	13 47 11.85	–61 20 18.8	6.6	-59.8		850	850	850	850	850		
309.92+0.48	13 47 11.85	–61 20 18.8	12	-59.8	138	157	157	144	173		1.20	+3
311.64–0.38	14 03 01.6	–61 44 06	6.6	+32.5		16.3	14.5	9.2	8.9	12.5	1.83	±9
311.64–0.38	14 03 01.6	–61 44 06	6.6	+34.2		6.3	5.0	2.9	2.7	5.5	2.33	±9
312.60+0.04	14 09 36.2	–61 02 57	6.6	-67.9		8.0	8.0	14.0	16.5	11.0	2.06	+6
316.64–0.09	14 40 31.6	–59 42 40	6.6	-19.8		117	130	101	102	137	1.34	±8
316.64–0.09	14 40 31.6	–59 42 40	12	-19.8	22	21	25	17	16		1.56	-6
316.81–0.06	14 41 39.3	–59 36 35	6.6	-42.1		11.0	9.0	7.3	5.8	6.0	1.90	-9
316.81–0.06	14 41 39.3	–59 36 35	12	-42.1		1.6		<0.2	<0.2		>8.0	-6
318.05+0.08	14 49 54.0	–58 56 43	6.6	-56.7		5.5	4.0	4.2	3.4	1.8	3.06	-18
318.05+0.08	14 49 54.0	–58 56 43	6.6	-53.7		1.4	1.1	1.1	1.8	2.6	2.36	+12
320.23–0.29	15 06 00.5	–58 14 14	6.6	-62.3		35.0	28.0	22.0	23.5	21.0	1.59	-6
320.23–0.29	15 06 00.5	–58 14 14	6.6	-70.4		2.5	2.7	2.5	3.3	4.5	1.80	+12
322.16+0.64	15 14 45.7	–56 27 28	6.6	-63.0		210	210	180	210	200	1.17	±3
322.16+0.64	15 14 45.7	–56 27 28	6.6	-63.4		170	160	145	162	160	1.17	-6
322.16+0.64	15 14 45.7	–56 27 28	12	-63.4	21	15.5	12.5	12.5	17.0		1.36	+3
327.29–0.58	15 49 16.0	–54 28 14	6.6	-48.5			0.9	3.7	2.3	0.3	12.30	-12
327.29–0.58	15 49 16.0	–54 28 14	12	-48.0		<0.2		1.3	0.8		>6.5	+6
331.13–0.24	16 07 10.8	–51 42 29	6.6	-84.4		31.2	23.3	15.5	25.0	28.5	2.01	-6
331.13–0.24	16 07 10.8	–51 42 29	6.6	-85.7		13.0	9.2	6.0	12.0	16.5	2.75	+12
331.13–0.24	16 07 10.8	–51 42 29	6.6	-90.8		2.5	3.5	21.0	28.0	3.0	11.20	±9
331.28–0.19	16 07 38.14	–51 34 12.2	6.6	-80.8		30	42	34	32	27	1.56	-12
331.28–0.19	16 07 38.14	–51 34 12.2	12	-78.8	147	145	131	145	141		1.11	±3
331.34–0.35	16 08 37.4	–51 38 32	6.6	-67.4		36	41	42	48	62	1.72	+18
331.34–0.35	16 08 37.4	–51 38 32	6.6	-65.2		85	102	92	80	55	1.85	-15
332.72–0.62	16 16 14.2	–50 53 18	6.6	-45.5		4.3	5.5	1.9	2.4	2.0	2.89	-3
335.79+0.17	16 26 06.0	–48 09 22	6.6	-49.0			154	135	121	102	1.51	-15
335.79+0.17	16 26 06.0	–48 09 22	6.6	-50.1			87	74	68	60	1.45	-15
335.79+0.17	16 26 06.0	–48 09 22	12	-47.5	55, 30	46	52	60	48		1.83	-19
336.99–0.03	16 31 51.9	–47 25 03	6.6	-125.8		25.0	38.0	28.1	17.5	11.0	3.45	-15
337.92–0.46	16 37 25.0	–47 01 21	6.6	-37.9		39	47	42	40	36	1.31	-18
337.92–0.46	16 37 25.0	–47 01 21	6.6	-38.8		32	39	39	40	44	1.38	+18
337.92–0.46	16 37 25.0	–47 01 21	6.6	-40.8		1.0	1.5	1.5	1.5	3.0	3.00	+18
338.46–0.25	16 38 36.1	–46 28 38	6.6	-50.5			92	82	75	86	1.23	-6
338.46–0.25	16 38 36.1	–46 28 38	6.6	-52.1			73	67	65	57	1.28	-18
339.62–0.12	16 42 26.5	–45 31 18	6.6	-36.9			51	41	44	38	1.34	-18
339.62–0.12	16 42 26.5	–45 31 18	12	-36.4		0.8	2.5	0.8			3.13	±3
340.79–0.10	16 46 38.35	–44 37 18.5	6.6	-106.7		390	290	166	188	300	2.35	-6
340.79–0.10	16 46 38.35	–44 37 18.5	12	-105.3	52	43	47	35	48		1.37	±3
341.22–0.21	16 48 42.1	–44 21 53	6.6	-37.9		146	166	205	137	168	1.50	-3
341.22–0.21	16 48 42.1	–44 21 53	12	-37.3	5.0	3.0	1.7	5.0	1.0		5.00	-3
345.00–0.22	17 01 38.5	–41 24 59	6.6	-22.5		290	448	315	365		1.53	±3
345.00–0.22	17 01 38.5	–41 24 59	12	-22.4	5.0	9.0	20.3	4.9	4.5		4.50	-6
345.50+0.35	17 00 54.2	–40 40 18	6.6	-19.7		58	61	53	43	43	1.42	-6
348.55–0.98	17 15 53.0	–39 00 53	6.6	-13.9		10	51	13	8	28	6.40	±4
348.55–0.98	17 15 53.0	–39 00 53	12	-10.1	20	5	5	5	5		4.00	-48
348.88+0.10	17 12 24.7	–38 06 49	6.6	-75.3		6.2	8.0	5.0	7.0	7.6	1.60	-3
348.88+0.10	17 12 24.7	–38 06 49	6.6	-76.4		3.6	3.0	3.4	3.4	4.4	1.48	+15
350.01+0.43	17 14 22.4	–37 00 18	6.6	-30.8		4.0	2.8	6.0	4.0	2.7	2.14	+3
351.77–0.54	17 23 20.67	–36 06 45.4	6.6	+1.2		250	220	120	260	170	2.17	±6
351.77–0.54	17 23 20.67	–36 06 45.4	6.6	+1.7		220	250	230	210	180	1.39	-15
351.77–0.54	17 23 20.67	–36 06 45.4	12	+1.8		4.4	8.5	5.4	3.4		2.50	-6
354.61+0.47	17 26 59.8	–33 11 34	6.6	-23.2		140	135	175	215	140	1.54	±9
354.61+0.47	17 26 59.8	–33 11 34	12	-23.1	10, 20	7.5	9.0	18.0	12.0		2.00	+1

Table 1 *(Continued)*

Methanol maser (l,b)	RA (1950) (h m s)	Dec (1950) (° ′ ″)	Trans Freq (GHz)	Velocity (km s^{-1})	Peak Flux density at different epochs* 88-91 (Jy)	92m (Jy)	92j (Jy)	92s (Jy)	92d (Jy)	93s (Jy)	Max/min intensity (ratio)	Time scale (month)
359.61–0.24	17 42 27.2	–29 22 18	6.6	+22.5		16	16	25	28	59	3.69	+18
359.61–0.24	17 42 27.2	–29 22 18	12	+22.5	14.5	13.1	13.5	12.2	16.2		1.33	+3
0.55–0.85	17 47 04.4	–28 53 39	6.6	+13.7	86		68	65	65	62		
0.55–0.85	17 47 04.4	–28 53 39	12	+13.8	8.0	3.5	4.1	3.8	3.7		1.17	±4
0.55–0.85	17 47 04.4	–28 53 39	12	+18.4	2.8	3.7	3.1	1.9	3.3		1.95	-6
5.90–0.43	17 57 36.9	–24 04 22	6.6	+10.4		5.6	8.5	5.2	13.9	3.4	2.67	+3
9.62+0.20	18 03 15.98	–20 31 52.9	6.6	+1.2	4870	4000	5100	4700	4700	4500	1.28	+3
9.62+0.20	18 03 15.98	–20 31 52.9	12	+1.3	90, 136	130	180	126	126		1.43	±12
10.47+0.03	18 05 40.0	–19 52 24	6.6	+75.0	823	60	70	47	60	100	17.50	-15
10.47+0.03	18 05 40.0	–19 52 24	12	+75.0	17.0	16.5	15.5	15.5	17.5		1.13	+6
12.68–0.18	18 10 59.6	–18 02 29	6.6	+57.7	456	350	520	440	510	450	1.49	±3
12.68–0.18	18 10 59.6	–18 02 29	12	+57.8	5.0	5.5	12.5	8.0	7.5		2.27	+3
12.68–0.18	18 10 59.6	–18 02 29	12	+57.0	12.0	9.5	16.5	9.5	9.0		1.83	-6
12.89+0.49	18 08 56.4	–17 32 14	6.6	+39.2	75		89	77	75	99	1.32	±8
12.89+0.49	18 08 56.4	–17 32 14	6.6	+29.1			<0.5	<0.5	<0.5	6.0	>12.0	+8
23.01–0.41	18 31 55.6	–09 03 09	6.6	+75.2	439	400	405	380	390	345	1.17	-15
23.01–0.41	18 31 55.6	–09 03 09	12	+75.0	25	28.0	29.5	26.5	23.0		1.28	-6
23.01–0.41	18 31 55.6	–09 03 09	12	+81.9	6	14	15	15	15		2.50	+50
23.44–0.18	18 31 55.3	–08 34 01	6.6	+103.6		34	37	42	48	38	1.41	+9
23.44–0.18	18 31 55.3	–08 34 01	12	+103.8	9, 13, 3	3.0	6.5	11.5	17.0		5.67	+9
24.33+0.14	18 32 26.8	–07 37 25	6.6	+110.2		6.4	6.8	6.4	10.8	14.7	2.30	+12
29.86–0.05	18 43 22.9	–02 48 26	6.6	+100.5		62	62	60	58	68	1.17	+9
29.86–0.05	18 43 22.9	–02 48 26	6.6	+100.9		47	43	42	42	45	1.12	±9
29.86–0.05	18 43 22.9	–02 48 26	12	+100.5	14.0	11.6	10.0	12.1	9.2		1.32	±3
29.86–0.05	18 43 22.9	–02 48 26	12	+100.9	14.0	10.6	9.0	10.9	7.0		1.56	±3
30.79+0.20	18 44 12.3	–01 52 04	6.6	+87.9			17.3		18.5	18.5		
30.79+0.20	18 44 12.3	–01 52 04	12	+87.9		8.7		11.4	12.1		1.39	+9
31.28+0.06	18 45 37.2	–01 30 00	6.6	+110.2	87	84	73	76	81	70	1.15	±4
31.28+0.06	18 45 37.2	–01 30 00	12	+110.3	110	74	65	56	59		1.32	-6
32.74–0.08	18 48 47.8	–00 15 50	6.6	+38.5	46		48	47	47	47		
32.74–0.08	18 48 47.8	–00 15 50	12	+38.6	6.0	7.4	6.6	4.7	4.9		1.57	-6
35.20–1.74	18 59 13.1	+01 09 07	6.6	+41.8	400	320	270	270	310	220	1.19	±7
35.20–1.74	18 59 13.1	+01 09 07	6.6	+42.3	556	490	430	500	560	540	1.30	+6
35.20–1.74	18 59 13.1	+01 09 07	12	+44.6	125, 150, 70	135	117	113	108		1.25	-9
59.78+0.06	19 41 03.6	+23 36 51	6.6	+25.0	103		60.0	46.0	42.0	24.5	2.45	-18
59.78+0.06	19 41 03.6	+23 36 51	6.6	+26.3			16.0	19.0	22.0	27.0	1.69	+15
59.78+0.06	19 41 03.6	+23 36 51	12	+27.1				15.5	14.8			

* 88-91 refers to early measurements in 1988-1991 identified more precisely in the notes to sources; the other columns refer to 1992 March, June, September, December and 1993 September

1988 has remained the same in 1992 but at velocity -10 km s^{-1} it has fallen from 20 Jy (1988 March) to 5 Jy (1992). A feature at velocity $-12 \cdot 7$ km s^{-1} appeared in 1992 June and disappeared within the next 3 months.

348·88+0·10 shows clear variations with some features increasing while others decrease.

350·01+0·43. Interestingly, the single, narrow feature seems relatively stable with the broader complex of several features flaring together and then decreasing.

351·77–0·54 is highly variable, especially the feature at velocity $+1 \cdot 2$ km s^{-1}, which has shown two maxima and two minima in our observations; the feature is strictly a very close blend, with a shoulder at slightly lower velocity, and neither has a 12-GHz counterpart. Also variable at 6·6 GHz is a feature at $+1 \cdot 7$ km s^{-1} which does not vary in synchronism with the other peak. It has a 12-GHz counterpart which flared at the same time as at 6·6 GHz, with larger fractional change.

354·61+0·47. The feature at velocity $-23\cdot1$ km s^{-1} is highly variable at 6·6 GHz, and even more so at 12 GHz. Caswell et al. (1993) found that the 12-GHz emission doubled in 5 weeks but subsequent observations have been too sparse to ascertain whether this time-scale is typical.

359·61−0·24 is variable at 6·6 GHz, especially at velocity $+22\cdot5$ km s^{-1}, with a large flare in 1993 September. It is also variable at 12 GHz, both relative to 1988 (C+93) and within the current observations, although we did not observe at the epoch of the 6·6-GHz major flare in 1993 September.

0·55−0·85. At 6·6 GHz the variations have been small, generally less than 10% but with perhaps a steady decrease of the peak since Menten's measurement of 86 Jy in 1991 June. At 12 GHz the feature at velocity $+18\cdot4$ km s^{-1} has increased by a factor of 2. At $+13\cdot8$ km s^{-1}, a feature decreased from 8 to 3·5 Jy from 1988 March (C+93) to 1992 March, and has subsequently remained fairly stable.

5·90−0·43. At 6·6 GHz there is one stable feature at velocity $+9\cdot2$ km s^{-1} but other features are highly variable, most notably at velocity $+10\cdot4$ km s^{-1}.

9·62+0·20. This has a peak intensity of approximately 5000 Jy, the strongest of any 6·6-GHz maser. Most features have remained quite stable, but there was a probable increase of at least 10% in the most intense feature in 1992 June. Menten's value of 4870 Jy in 1991 June also suggests fluctuations exceeding 10%. At 12 GHz the two main features (blended) varied markedly between 1988 April and 1989 November (C+93), and variations continue, with the highest intensity occurring in 1992 June (the same epoch as the 6·6-GHz maximum).

10·47+0·03. The strongest 6·6-GHz feature in 10·47+0·03, at $+75$ km s^{-1}, is variable, with our measurements ranging from 47 to 100 Jy. Menten (1991b), who lists the source as W31(1), reports a peak value of 823 Jy on 1991 June 2, while other features have intensities similar to our values (Menten, personal communication). Thus the feature decreased by an order of magnitude in 9 months and is one of the most variable strong features discovered. At 12 GHz it is also variable, but by less than 20% in the period of our observations.

12·68−0·18. At 6·6 GHz the largest change was at velocity $+57\cdot7$ km s^{-1}. This feature had a peak of 456 Jy in 1991 June (Menten 1991b), decreased to 350 Jy in 1992 March (spectrum not plotted), and then increased to 520 Jy in 1992 June. The latter change was paralleled by an increase by a larger amount at 12 GHz for both this feature and for another at velocity $+57\cdot0$ km s^{-1}.

12·89+0·49. Variability is seen in many features, including the strongest one at velocity $+39\cdot2$ km s^{-1}, which had minimum values in 1991 June (75 Jy according to Menten 1991b) and 1992 December, and maxima of 89 and 99 Jy in 1992 June and 1993 September respectively. The feature at $+35\cdot6$ km s^{-1} is stable and the most variable feature is at $+29\cdot1$ km s^{-1} which became visible for the first time in 1993 September. At 12 GHz there is a strong counterpart to the 6·6-GHz peak, but we observed it only in 1992 September (62 Jy) and in 1992 December (55 Jy).

23·01−0·41. At 6·6 GHz, Menten's (1991b) observations showed a peak intensity of 439 Jy in 1991 June which was 10% greater than our later measurements. There have been no strong variations apart from the shoulder near velocity $+75$ km s^{-1}, which changed in 1993 September to indicate a blended feature which had decreased considerably. The 12-GHz emission at velocity $+82$ km s^{-1} increased from 6 Jy (1988 April) to 14 Jy (1992 March) but has since remained stable; one other feature, the strongest, at velocity $+75$ km s^{-1}, has varied by more than 20%.

23·44−0·18 has many variable features at 6·6 GHz and is also strongly variable at 12 GHz (C+93), especially at velocity $+103\cdot8$ km s^{-1}. The 6·6-GHz feature nearest to this has paralleled the 12-GHz variability, but with smaller amplitude.

24·33+0·14 has highly variable features, with all of them strongest in 1993 September; some increased by a factor of 10 in the 9 months since 1992 December. 12-GHz observations, made only in 1992 December, show a peak of 20 Jy at velocity $+110$ km s^{-1}. It is one of the few methanol masers in which the 12-GHz peak intensity exceeds that at 6·6 GHz.

29·86−0·05 is slightly variable in most features at 6·6 GHz and is more variable at 12 GHz.

30·79+0·20 is clearly variable at 6·6 GHz with some features increasing and some decreasing by up to 20%. It is more variable at 12 GHz, where all features increased at the same time, as is clear from the spectra shown.

31·28+0·06. Variability at 6·6 GHz is not large but is clear both within our data set and relative to Menten's 1991 June spectrum, with some features increasing while others decreased. At 12 GHz the steady decline in the peak at velocity $+110\cdot3$ km s^{-1} paralleled the change at 6·6 GHz.

32·74−0·08 is only slightly variable at 6·6 GHz, with Menten's 1991 June peak value almost the same as our 1992 values. At 12 GHz, strong variations are clearly seen in the feature at velocity $+38\cdot6$ km s^{-1}.

35·20−1·74. At 6·6 GHz the two variable features tabulated vary differently, although the initial decline relative to Menten's 1991 June measurement was similar. At 12 GHz the most dramatic changes were in 1988/9 but have continued at a lesser level.

59·78+0·06 shows clear variability at 6·6 GHz with some features stable, some increasing and some decreasing monotonically from 1992 June through December to 1993 September. Menten's (1991b) peak value of 103 Jy in 1991 June suggests that the decline in the once strongest feature may have been monotonic from 1991 June through to 1993 September. The 12-GHz emission (observed only in 1992 September and December) is only slightly variable (e.g. at velocity $+17$ km s^{-1} the intensity fell from 4 to 3 Jy) and coincides with the non-varying 6·6-GHz features. The strongest 12-GHz peak is a blend of two features, as can be seen from the distinct shoulder of emission.

5. Discussion

(5a) Timescales and Amplitude of the Variations

The principal purposes of our observations were to detect new methanol masers, measure their positions, and investigate their general properties, so as to establish the most common varieties and to recognise individuals which deviate significantly from the norm. The resulting data set is now proving to be valuable for variability investigations, since changes were commonly seen on the timescale of the 3-month interval between observing sessions. Fluctuations on much shorter timescales are not common: we found no variability on the 20-minute timescale in which our positioning measurements were made; nor did we detect changes on the timescale of 2 or 3 days when system-performance checks were made on strong sources at these intervals.

Within sources possessing complex spectra, if there are variations in the intensity of only some features, we can readily recognise this even at a level of a few per cent, since relative variability does not rely on the accuracy of the absolute calibration and is limited only by the noise level. Indeed, amongst sources with at least 10 velocity components, we usually find at least one component displaying variability on a timescale of 3 months.

We now summarise the characteristics of variability as exhibited in our sample:

- Features which have initially increased in intensity will, necessarily, eventually decrease; most have done so within the time-span of our observations.
- Features which decrease in intensity will not necessarily recover—they could fade and never return. However, most of them have recovered within our observing time-span.
- Some sources, especially those observed over several years, have features which have shown two maxima or two minima, e.g. 351·77−0·54 and 12·89+0·49.
- Maxima and minima appear equally likely to persist over two of our successive observing epochs and thus we find no evidence for a systematic difference between the rate of increase in intensity and its rate of decrease.
- Although the fluctuations do not appear to be strictly periodic, from the previous four characteristics we suggest that the variations are best described as quasi-periodic rather than as a succession of flares.
- The timescales for the variations have a median period of 16 months (taken as twice the median between maximum and minimum). It is similar at both 6·6 and 12 GHz, but perhaps slightly smaller at 12 GHz.
- Where many features are seen in a spectrum, a variation of intensity may be present in all features, in none, or any fraction in between. For example, only one feature seems to be variable in the source 312·60+0·04.
- In the case of a few sources, all variable features within a source are seen to increase and decrease at the same epochs, e.g. 290·37+1·66, 311·64−0·38, 24·33+0·14 and 30·79+0·20.
- In many sources, while some features are seen to increase, others decrease, e.g. in 294·52−1·62, 318·05+0·08, 320·23−0·29, 331·13−0·24, 331·34−0·35, 337·92−0·46, 348·88+0·10, 351·77−0·54, 31·28+0·06 and 59·78+0·06.
- In some sources, prominent features at the same velocity are seen at both 6·6 and 12 GHz; in some instances their variations are synchronised, e.g. in 316·64−0·09, 351·77−0·54 and 31·28+0·06.
- Where a variable feature is present at both 6·6 and 12 GHz (16 excellent examples), the percentage variability at 12 GHz is almost always greater, as shown by 316·64−0·09, 341·22−0·21, 345·00−0·22, 351·77−0·54, 9·62+0·20, 12·68−0·18, 23·44−0·18, 29·86−0·05 and 31·28+0·06. A notable exception to this generalisation occurs in the strongest feature of 10·47+0·03, but in total, only two of the 16 examples are more variable at 6·6 GHz.

The 48 sources studied in this paper have been selected for their relatively high variability, but in the whole sample of 245 sources of C+95a, and considering all features, nearly 3/4 of the features are not significantly variable. Even for the features of Table 1 which are generally the most variable, more than 60% have maximum-to-minimum ratios of less than 2. Thus, overall, the amplitude of variation is low and suggests that the maser gain is only weakly dependent on path length. This, in turn, is usually argued to be the signature of saturated masers, in contrast to unsaturated masers which show an exponential dependence of intensity with path length.

If the pump is global, as in the pumping by submillimetre photons according to the scheme proposed by Cragg et al. (1992), then the few instances of variability synchronised between all features may be due to a variation in the pump level. A remarkable, but rare, example of such global variability is seen in 291·28–0·71, in which all the strong features at 12 GHz seen in 1992 were at least an order of magnitude weaker 3 years previously. More commonly, features within a source do not vary synchronously and the intensity variability is more likely due to variability in the path length available for the maser, which is affected most simply by motions within the source. [Small phase lags can occur even if the variability is caused by changes in the output of a central pump. For example, masers in the outer shells of late-type stars can exhibit light travel time differences as large as a month (Chapman et al. 1993). However light travel time differences are unlikely to be an explanation for the differences we see on the scale of many months.] The methanol variability has some characteristics in common with that of H_2O masers, and our suggested explanations are similar to those proposed for H_2O variability by Peng (1989a,b).

(5b) Comparison of 6·6- and 12-GHz Masers

Comparison of spectra of the 6·6- and 12-GHz methanol transitions shows that the 12-GHz peak intensity is usually much lower than the 6·6-GHz intensity but the 12-GHz peaks often agree closely in velocity with major 6·6-GHz peaks. However, there are some strong 6·6-GHz peaks with no detectable 12-GHz counterparts and vice versa.

In Table 1, where we list 20 instances of corresponding features on both transitions, it can be seen that in half of these cases the 12-GHz feature is at slightly higher velocity than the 6·6-GHz feature. In a previous paper (C+95a), we remarked that there is probably a small error in the currently adopted rest frequencies such that the 12-GHz features appear to be at larger velocity by 0·07 km s^{-1}. Since we have rounded the velocities of Table 1 to the nearest 0·1 km s^{-1}, the matching features at 12 GHz are often listed with more positive velocity than 6·6-GHz features by this amount.

Although our single-dish data can confirm only that features on the two transitions often coincide in velocity, it has been shown (Norris et al. 1993) that in at least some cases they are also coincident spatially. This would be entirely consistent with the common pumping scheme for the two transitions envisaged by Cragg et al. (1992). The relative intensities of the transitions could then indicate the physical conditions in the masing region.

In Section 5a we noted that the variability of 12-GHz masers is generally greater than for matching 6·6-GHz features. This could be most simply explained if the 12-GHz transition is generally somewhat less saturated than the 6·6-GHz transition. With further development of the pumping theory, this too could yield more details of the physical conditions. The increased variability at 12 GHz compared to 6·6 GHz, although clear when comparing matching features, is not readily seen from any other statistics. For example, the maximum-to-minimum ratios in Table 1 have the same median value, 1·6, for both the 6·6- and the 12-GHz features taken separately. In addition, for the populations as a whole, a fraction 0·28 of the total 6·6-GHz features were found to be significantly variable (C+95a) and an almost identical fraction of 12-GHz features are variable (Caswell et al. 1995b).

6. Conclusions

We have shown that short-term variability of 6·6-GHz masers is very common, as is also true for the closely related 12-GHz masers (C+93). We have also singled out some masers whose marked variability deserves investigation on a longer timescale. Some possible generalisations have been investigated and lead us to conclude that variations are best described as quasi-periodic. We suggest that the variations are most commonly due to path-length changes in the maser-emitting region which could be caused by large-scale motions. The generally higher variability of 12-GHz masers probably indicates that they are less saturated than the corresponding 6·6-GHz masers.

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