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Time variations of interstellar water masers in H II regions

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Summary. Fourteen water maser sources associated with H II regions have been monitored over the period 1974 September–1977 May. Time variations have been observed with a range of time-scales from days to years. A statistical analysis of the short- and long-term variations is performed and related variability in features of similar velocity is examined. The time variations must be due to changes in the pump input, geometry or other physical properties of the maser regions but at present no adequate theory exists to describe the complex behaviour observed.

1 Introduction

Many of the 100 or more sources of water vapour emission at 22.2 GHz now known are associated with regions of star formation in the Galaxy. The spectra of most of these sources are complex and all show variations with time-scales ranging from several months to a few days. Interferometric studies of W3, W3(OH), Orion A, Sgr B2, W49 and NGC 7538 (Moran *et al.* 1973; Genzel *et al.* 1978) have shown that the H_2O emission originates in 'centres of activity' which may be associated with the envelopes of recently formed O and B stars. These active sites have dimensions typically $\sim 10^{16}$ cm and are distributed over regions $\sim 10^{17}$ cm in size. Individual spectral features appear as separate components less than 10^{13} cm in size and clustered in an apprently random manner about a centre of activity. The brightest of these components have brightness temperatures $\sim 10^{14}$ K.

Previous studies of time variations in water vapour sources associated with H II regions by Sullivan (1971, 1973) and Gammon (1976) have revealed variability on time-scales of 10^6–10^7 s. Sullivan monitored nine sources over a period of 14 months and Gammon observed W49(H_2O) for 13 months. In an attempt to gather more complete information on the variability of interstellar water masers, we have monitored 18 sources for the 32-month period 1974 September–1977 May. The sources selected were the strongest known at the beginning of the programme above declination $-20°$. The observations of the four strongest sources in this list have been published previously (Little, White & Riley 1977) and will not be discussed further here. Table 1 gives a list of the 14 remaining sources:

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Table 1. The 14 H_2O maser sources monitored in the period 1974 September–1977 May.

SOURCE	RIGHT ASCENSION (1950.0) h	m	s	DECLINATION (1950.0) °	'	"	DISTANCE (kpc)	HIGHEST FLUX (Jy) 1969-70	HIGHEST FLUX (Jy) 1974-77	VELOCITY RANGE OBSERVED (km s^{-1})	VELOCITY WIDTH (km s^{-1})	No. OF COMPONENTS 1974-77
W3	02	21	53	61	52	22	3	3,000	1,560	-48 to -25	11	>7
NGC 1333	03	25	59	31	06	05	0.5		160	-40 to 0	3	2
S 255	06	09	58	18	00	02	1-3		780	-10 to +40	7	2
S 269	06	11	47	13	50	24	2		200	0 to +40	1	1
W 31	18	07	34	-19	56	30	6		1,420	-10 to +10	6	4
W 33	18	10	54	-18	03	12	4.5		235	+48 to +68	2	1
M 17	18	17	29	-16	13	42	2.5	3,200	150	-17 to +27	1	1
ON 1	20	08	10	31	22	39	6	500	515	-10 to +30	9	4
ON 2	20	19	51	37	16	24	5.5		400	-21 to +23	20	>5
CRL 2591	20	27	36	40	01	11	>2		580	-40 to 0	17	5
W 75 S	20	37	15	42	12	00	3	5,000	655	-20 to +20	9	4
S 140	22	17	42	63	03	45	-		530	-20 to +20	26	3
S 152	22	55	38	58	33	02	3.2		55	-61 to -42	-	1
NGC 7538	23	11	36	61	10	20	3.5		540	-65 to -45	10	3

column 1 contains the source name; columns 2 and 3 the position observed; column 4 the distance; column 5 the flux of the strongest component observed by Sullivan (1973) and column 6 the highest flux observed during the present observations in the velocity range indicated in column 7. The sensitivity limit for detection of an individual spectral component is typically 25 Jy. Column 8 gives the overall velocity width of the spectrum and column 9 the total number of separate features observed to this flux limit. Observations made with greater sensitivity (e.g. Genzel & Downes 1977) have often shown the existence of a greater number of features with a larger velocity spread than we have tabulated.

2 The observations

The observations were performed with the 25-m radio telescope at the SRC Chilbolton Observatory. The equipment and observing technique have been described elsewhere (Little *et al.* 1977). All velocities given are relative to the local standard of rest unless otherwise indicated and are accurate to ± 0.3 km/s. The velocity resolution is typically 0.4 km/s but is stated in the figure captions to the spectra. An estimate of the errors in the flux measurements determined from their day-to-day reproducibility suggests a relative accuracy between the six weekly intervals at which the monitoring took place (~ 15 per cent). The main factors contributing to this error are uncertainty in the atmospheric water vapour correction (~ 5 per cent) and the estimate of the receiver noise temperature (~ 10 per cent).

W 3

The W3 region is a large complex of radio, molecular line and infrared sources in the Perseus arm. The whole region is highly obscured and is believed to contain many sites of active star formation. Radio and infrared maps of W3 have revealed the presence of 10 distinct radio sources and seven infrared sources (Sullivan & Downes 1973; Wynn-Williams 1972; Harten 1976; Harris & Scott 1976).

Water vapour emission was detected from W3 by Knowles *et al.* (1969) and monitored by Sullivan (1973) from 1969 February–1970 March. Three main spectral features dominated these spectra during this period, having radial velocities of −40.8, −35.6 and −33.8 km/s, as well as a highly blended ridge of emission over the velocity range −44 to −39 km/s. The basic spectral shape has remained remarkably consistent over the five-year interval between Sullivan's monitoring and our observations. In particular the features with radial velocities ~ −40.8, −35.6 and −33.8 persist. The −40.8 km/s feature which dominated Sullivan's spectra, declined steadily from ~ 1600 to ~ 400 Jy over our monitoring period, remaining the most intense component at all times except in 1976 November when the −35.6 km/s component grew to ~ 930 Jy.

The intensity variations for individual features are plotted in Fig. 1. A general decline in integrated flux is evident over the monitoring period. To illustrate this more clearly, we have integrated the spectra over periods of ~ 1 yr, with an effective velocity resolution of ~ 0.5 km/s. These flux averages are shown in Fig. 2 and are compared with a similar average taken from Sullivan's data. The integrated flux fell by a factor of 2.1 between 1974–75 and 1975–76 and by a factor of 2.5 between 1969–70 and 1975–76. Similar variations in the mean flux of water maser sources were observed in W49 and W51 (Little *et al.* 1977) and are discussed later in this paper.

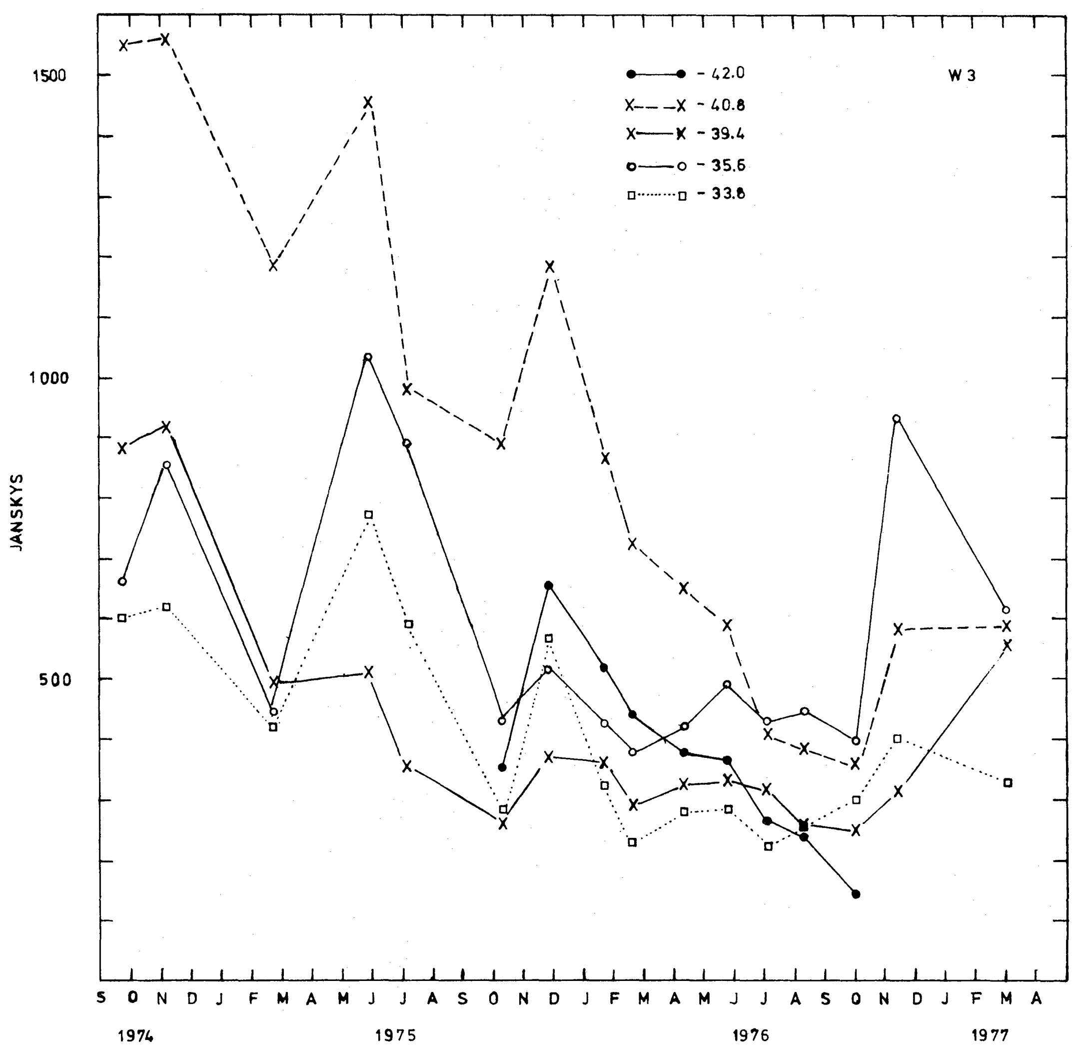


Figure 1. Intensity variations of the main features in the spectrum of W3.

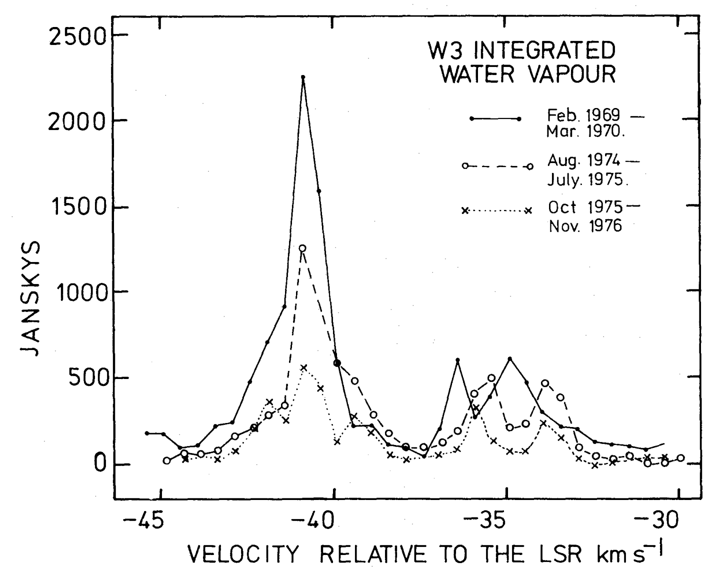


Figure 2. Time averages of spectra of W3, with velocity resolution 0.4 km/s.

NGC 1333

Water vapour emission was detected near NGC 1333 by Lo, Burke & Haschick (1975), and subsequently confirmed by Dickinson, Kojoian & Strom (1974) to come from a position lying close to the Herbig–Haro object HH-11. Further observations by White & Little (1975) showed that this water vapour source exhibited extremely rapid variability, with *e*-folding times as short as 3 day. Lo *et al.* (1975) have suggested that this rapidly variable water vapour emission originates in a region where the radiatively driven stellar wind from an embedded star is interacting with circumstellar neutral material. The resulting turbulent motions, arising from Rayleigh–Taylor instabilities at the wind–cloud interface, alter the effective maser path lengths and give rise to the extreme variability observed.

We were able to detect the source between 1975 February and July, but the source became undetectable in subsequent monitoring. The nominal pointing position (Table 1) lies 24 arcsec from the mean position more recently measured by Lo *et al.* (1976).

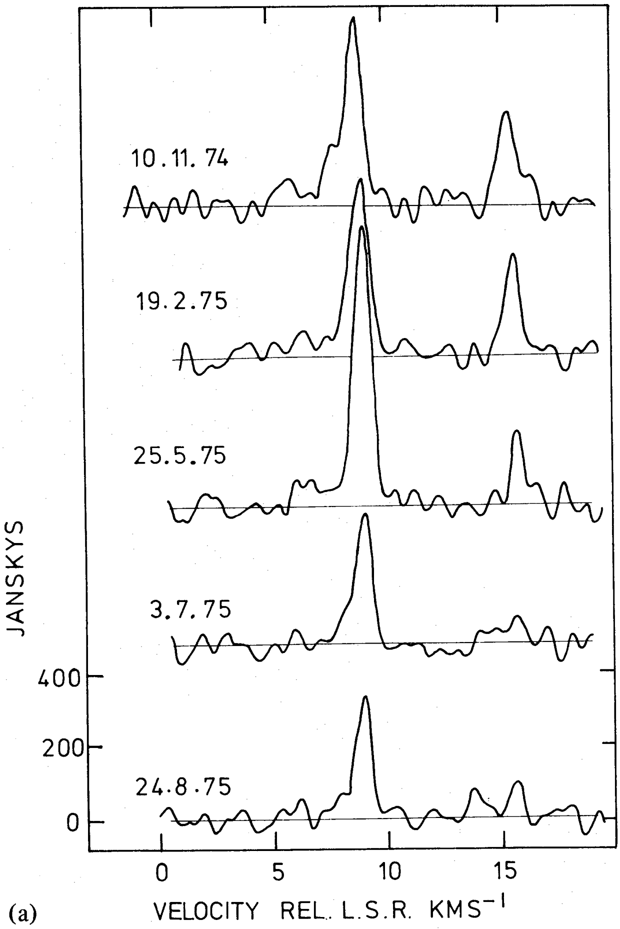
S255

S255 is a compact H II region which lies towards a complex of thermal radio sources (Lo 1974). An H_2O maser source was discovered by Lo & Burke (1973) to lie between S255 and S257, although no continuum radio emission >5 mJy was detected at the maser site. A bright CO hotspot with a radial velocity of 7.8 km/s has been detected lying close to the water maser site (Blair, Peters & van den Bout 1975).

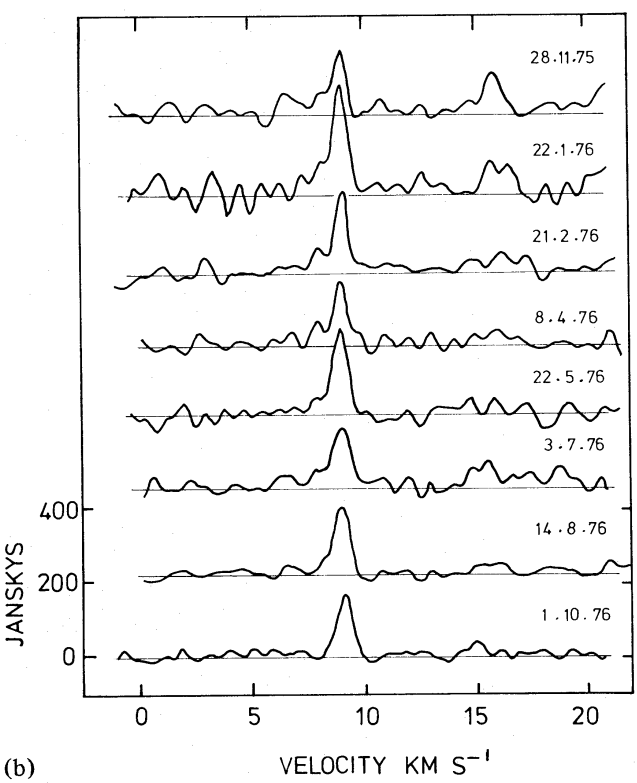
The two water line components with velocities +8.7 and +15.9 km/s detected by Lo & Burke are still visible in the spectra taken during 1974–77 (Fig. 3). Both components have appeared considerably brighter than at the time of the original detection, the +8.7 km/s feature flaring to ~800 Jy in 1975 May. A more recent spectrum by Genzel & Downes (1977) in 1977 January showed that this feature had fallen to ~75 Jy.

S269

S269 is a bright compact H II region associated with a type I OH maser and a weak extended infrared source. Weak H_2O emission was discovered by Lo & Burke (1973), who found one



(a)



(b)

Figure 3. Spectra of S255 with velocity resolution 0.4 km/s.

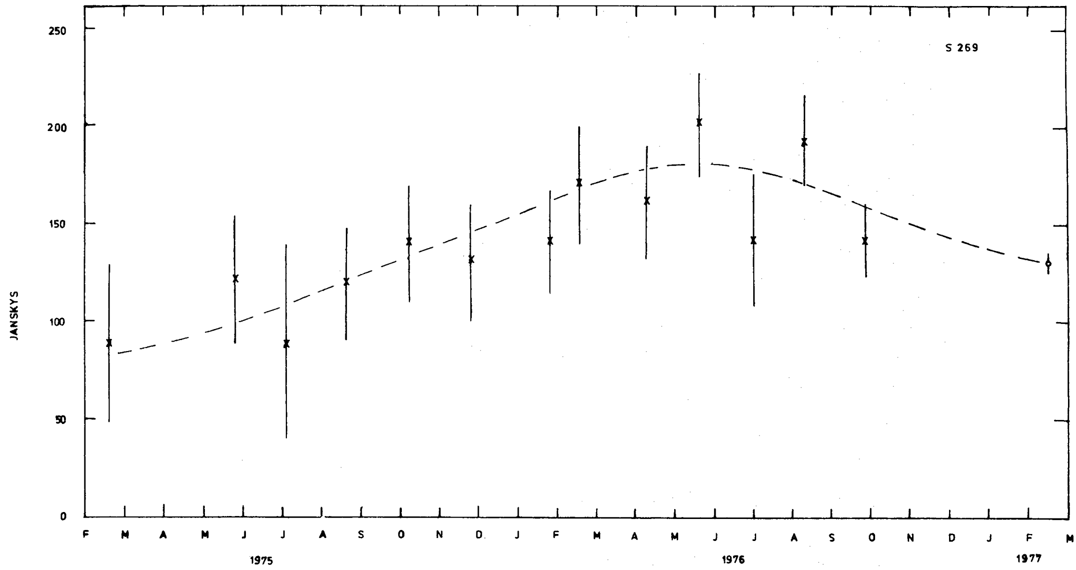


Figure 4. Intensity variation of the single component in the spectrum of S269 at a velocity of 16.7 km/s. The flux measurement in 1977 February is from Genzel & Downes (1977).

spectral component of intensity ~ 70 Jy with radial velocity + 16.5 km/s as well as a weaker blend of emission of flux ~ 30 Jy at a radial velocity of + 18.5 km/s.

The present observations during 1975 and 1976 show a single spectral feature with average radial velocity + 16.7 km/s which gradually increased in flux through 1975 to a peak intensity of 180 Jy in 1976 May, after which the flux began to decline. The flux variations of the 16.7 km/s component are shown in Fig. 4, the error bars representing the peak to peak noise level in the spectrum over the velocity range − 5 to + 27 km/s. When the source was observed by Genzel & Downes in 1977 February the flux of the main component had fallen to ~ 130 Jy.

W31

Water vapour emission was detected from W31 by Turner & Rubin (1971) and by Johnston *et al.* (1972). Yngvesson *et al.* (1975) have reported further observations made during 1973, when three spectral components were visible with radial velocities of − 1.4, + 0.8 and + 4.0 km/s.

The shape of the spectrum during most of 1975 remained similar to that determined by Yngvesson *et al.* After 1976 January, the − 2.0 km/s component, which had dominated the spectrum both in 1973 and throughout 1975 decreased sharply in intensity, to disappear into the blend of emission between − 2 and + 3 km/s. Two other features were visible with velocities − 0.5 and + 1.0 km/s. The variations are displayed in Fig. 5. Between 1975 February and 1976 September the integrated water vapour emission fell by a factor of 6 over the velocity range − 4 to + 3 km/s.

W33B

Water vapour emission from this type I OH source (Robinson, Goss & Manchester 1970) was detected during 1972 by Johnston *et al.* (1972). Two spectral features of radial velocities + 59.6 and + 57.3 km/s were observed, both with an intensity of ~ 75 Jy. An improved position for W33 was reported by Caswell *et al.* (1976), and found to lie 71 arcsec

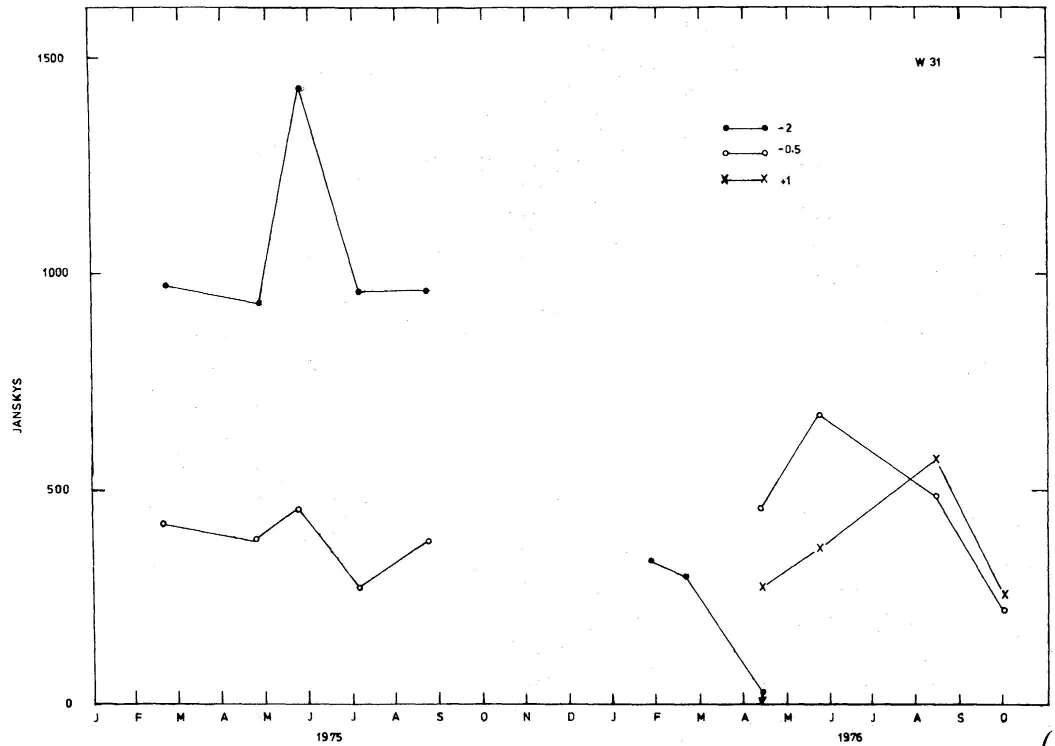


Figure 5. Intensity variations of the main features in the spectrum of W31.

from our pointing position. Several other weaker sources have been detected nearby (Genzel & Downes 1977), although they lie outside the half-power beam width of the Chilbolton telescope. If the emission we have detected originates from the position of Caswell *et al.*, our flux scale should be doubled.

Throughout the whole period of our monitoring, only one spectral feature was detected, at a radial velocity of + 58 km/s. A plot of the intensity variations is shown in Fig. 6. The intensity of the + 58 km/s feature varied slowly between 230 and ~ 40 Jy.

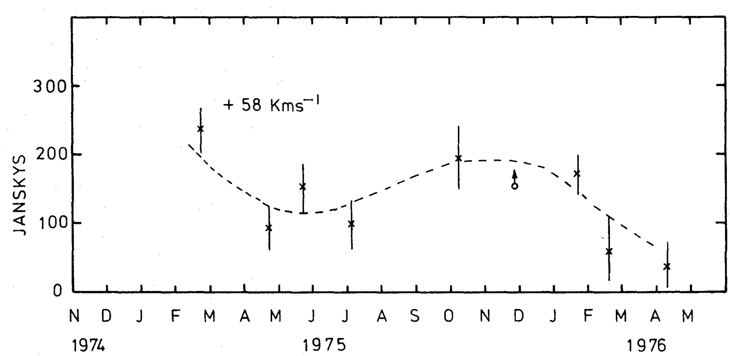


Figure 6. Intensity variation of the + 58 km/s component in W33B.

M17

The M17 molecular cloud was found to contain a strong H_2O maser in 1972 (Johnston, Sloanaker & Bologna 1973). A component was detected at a radial velocity of + 13.4 km/s with an intensity of ~ 3200 Jy, as well as a weaker feature of 100 Jy at + 0.6 km/s. A second water vapour source was reported by Lada *et al.* (1976), separated by ~ 2 arcmin from the position of Johnston *et al.* This new source was resolved into two further sources by Genzel & Downes (1977).

We detected M17 on only two occasions in 1975 July and 1976 January. A single feature was present in 1976 January at a radial velocity of + 14 km/s, with an intensity of 125 Jy. A subsequent observation by Genzel & Downes (1977), made in 1976 October, shows that this feature was still present with an intensity of ~ 120 Jy, and that a stronger feature had appeared at a radial velocity of + 22 km/s.

Observations by ourselves and other groups indicate that M17 is currently not a strong water vapour source. Early observations during 1969–70 (Sullivan 1971) and 1971 (Johnston *et al.* 1973) reported upper limits of < 20 Jy. The strong emission reported in 1972 August (Johnston *et al.* 1973) shows that this source is capable of large variations in its water maser emission.

ON1

ON1 is a very strong type I OH source associated with an isolated, compact H II region (Matthews *et al.* 1973). Water maser emission from ON1 was detected by Knowles *et al.* (1969) and Turner *et al.* (1970). The position of the maser site was measured by Baudry, Forster & Welch (1974) and Genzel & Downes (1977), and found to be coincident with the compact H II region. Further observations by Yngvesson *et al.* (1975) and Cato *et al.* (1976) showed that there were at least seven spectral components lying in the velocity range +4 to + 26 km/s, with further weak high velocity features extending as far as − 70 km/s.

The spectra observed in 1975 and 1976 are dominated by two groups of features in the velocity intervals +9 to +12 km/s and +13 to +17 km/s. The heavy blending of adjacent spectral components makes it difficult to construct a variability plot for this source, but we have attempted to do so for those features which at some time during the monitoring period were resolved separately. This plot is shown in Fig. 7.

We have compared the spectra obtained by Sullivan (1973) with the present observations to obtain average integrated profiles over the whole monitoring period. This comparison is shown in Fig. 8 where it can be seen that the integrated luminosity was similar in 1975–76 to that in 1969–70.

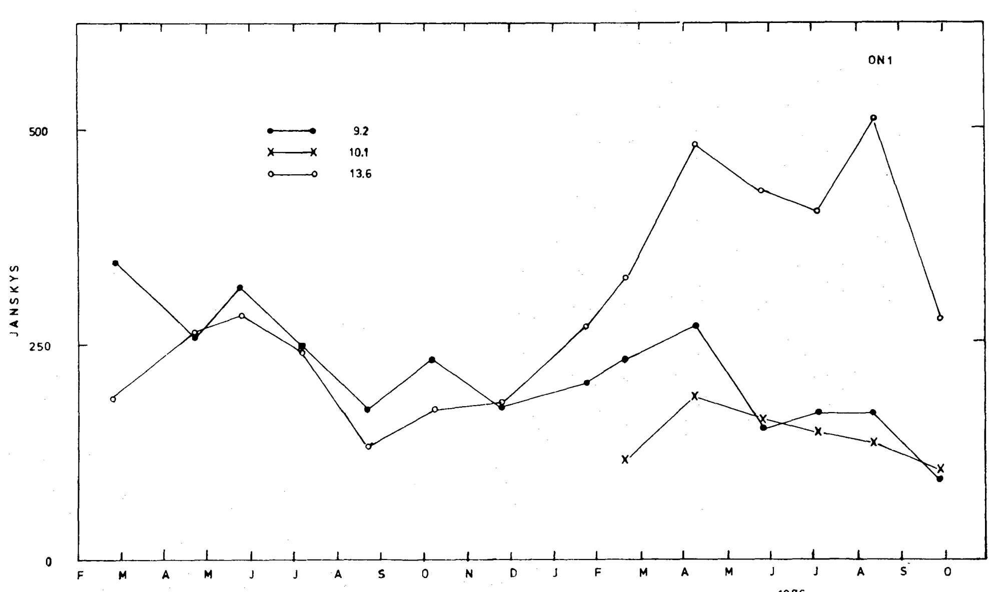


Figure 7. Intensity variations for three separate components in ON1.

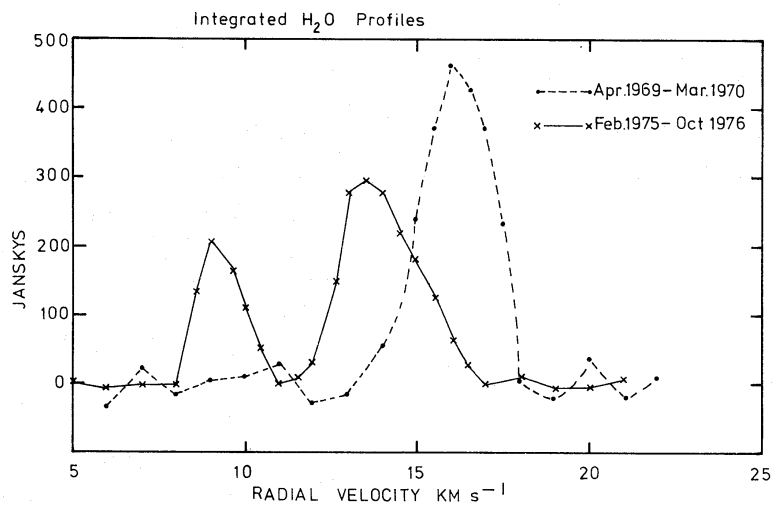


Figure 8. A comparison of the average spectra over the period 1975 February–1976 October with that of Sullivan (1973) over the period 1969 April–1970 March for ON1.

ON2

ON2 is a strong type I OH maser source discovered in the Onsala survey (Elldér & Rönnäng 1969). Johnston *et al.* (1973) reported the detection of a weak H_2O maser lying close to the position of the OH source. Cato *et al.* (1976) and Genzel & Downes (1977) have shown that the emission comes from two spatially distinct regions separated by 79 arcsec. Our pointing position for ON2 lies halfway between those two sources. To correct for the effect of the beam response, fluxes for the two sources ON2(S) and ON2(N) should be multiplied by factors 1.2 and 1.1 respectively. The relatively large size of our beam makes it impossible to separate these two sources completely and we therefore present uncorrected spectra taken between 1974 and 1976 in Fig. 9. The spectral features cover the velocity range -12 to $+10$ km/s. The two strongest features having radial velocities -11.5 and $+4.5$ km/s had peak intensities of ~ 400 Jy. The data of Cato *et al.* and Genzel & Downes show that the emission at -11.5 km/s probably comes from ON2(S), whereas the blended emission with velocities > 0 km/s comes predominately from ON2(N).

CRL 2591

This infrared source was detected in the AFCRL survey (Walker & Price 1975). The detection of water vapour emission in this source was reported by White *et al.* (1975) and confirmed by Lo *et al.* (1975). Three main features dominated the spectra during 1974 and 1975, having radial velocities -24.5, -22.5 to -21 and -11 km/s. We were unable to detect the bright components reported by Lo *et al.* (1975).

The source remained in a state of high integrated luminosity from 1974 September until the beginning of 1976, when the integrated luminosity fell by a factor of ~ 4, remaining in this low state through most of 1976. By 1977 April, however, the source had returned to its high state with two components at -23 and -21 km/s.

We note the apparent drifting in frequency of the -21 km/s component between 1974 November and 1975 February. Frequency drifting of this nature is probably the result of superimposing several velocity features which are varying in amplitude in a related manner with a progressive phase shift. Similar behaviour has been noted in Orion A and W51 (Little *et al.* 1977).

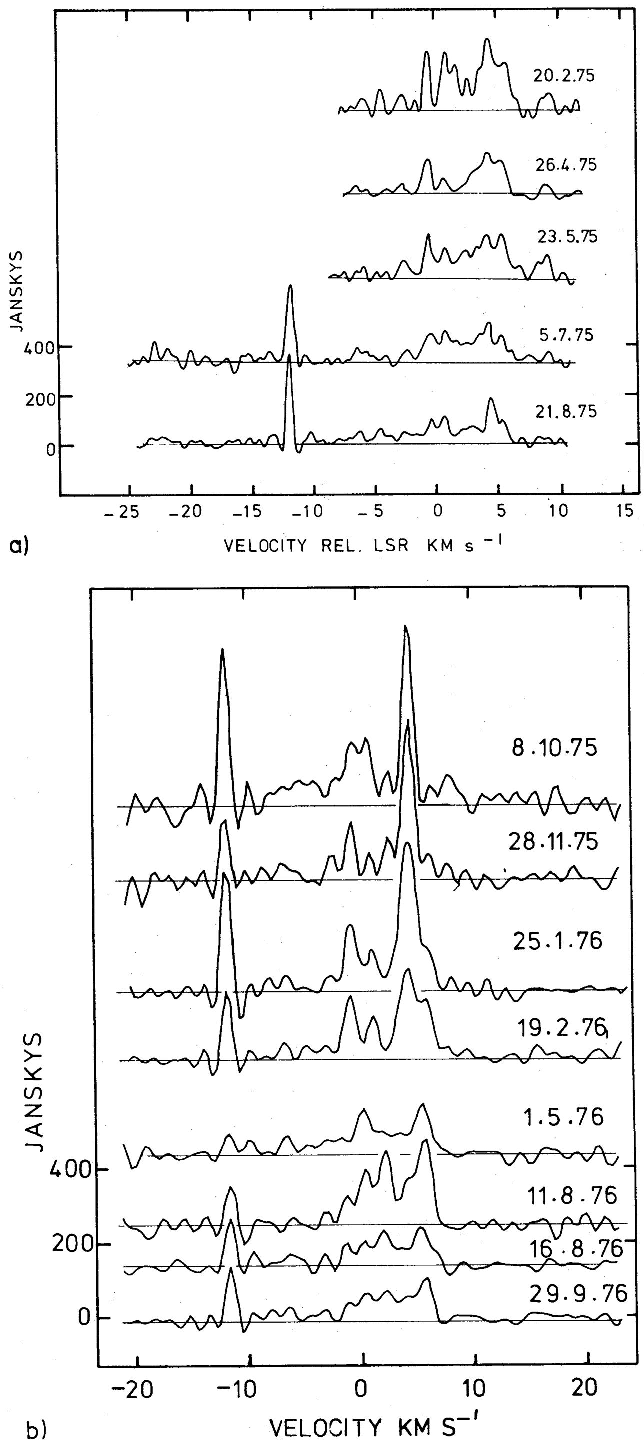


Figure 9. Spectra of ON2 (a) and (b) with velocity resolution 0.8 km/s showing a component at − 11.5 km/s probably associated with ON2(S) and a group of components > 0 km/s predominantly from ON2(N).

The intensity variations of the −24.5, −22.5 and −21.0 km/s features are plotted in Fig. 10.

W75S

W75S lies in a complex region close to the well-studied molecular source DR21. Knowles *et al.* (1969) and Meeks *et al.* (1969) independently reported H_2O emission close to the type

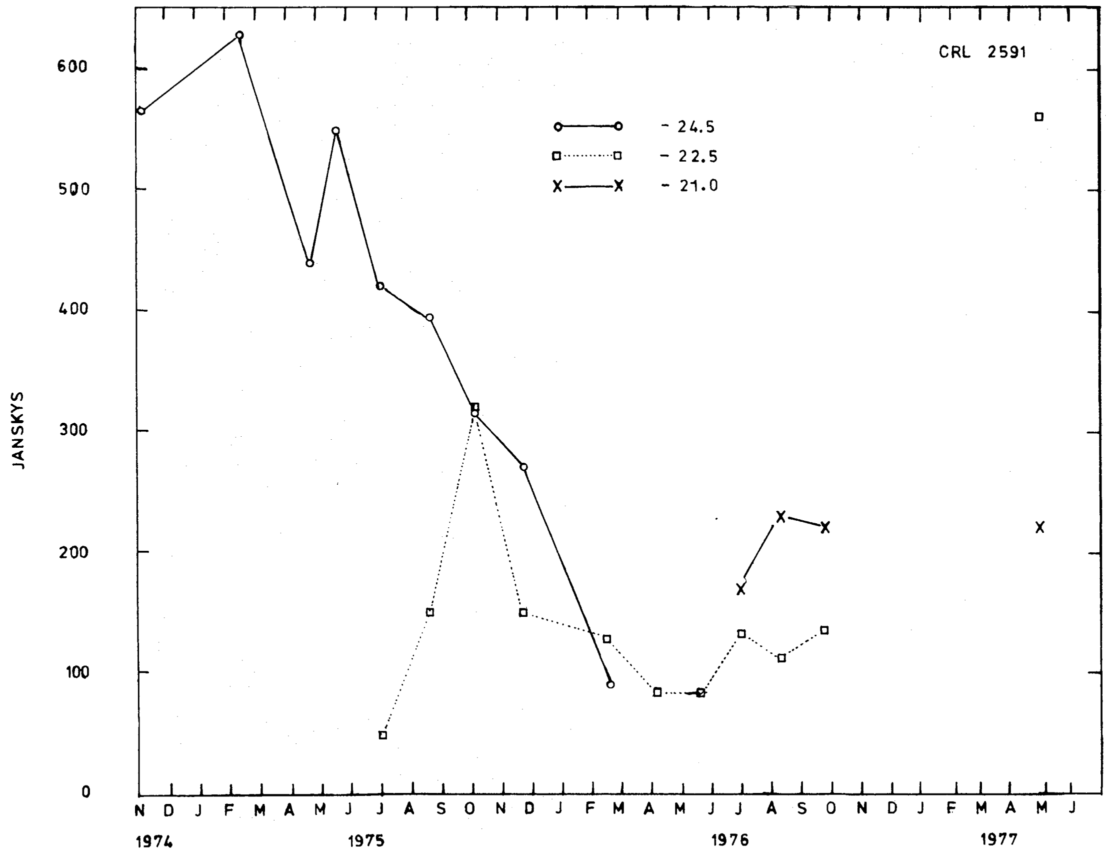


Figure 10. Intensity variations of the three main components in CRL 2591.

I OH source W75S. During Sullivan's observations of 1969 February–1970 March, W75S showed a strong emission line of ~5000 Jy at a radial velocity of +3 km/s, which rapidly decreased in intensity to leave a weaker blend of emission in the velocity range 0 to +3 km/s, at an intensity of ~500 Jy. Further observations by Cato *et al.* (1976) and Genzel & Downes (1977) showed that there were three separate water maser sites in W75.

Six strong features dominated the spectra observed between 1974 and 1977, at radial velocities of −9.0, −7.0, −5.7, −4.6, +0.5 and +3.0 km/s. At its most intense in 1976 February, the +0.5 km/s component had an intensity of 630 Jy. The intensity variations of these components are plotted in Fig. 11.

Genzel & Downes (1977) have determined that the H_2O maser site lies 23 arcsec from our pointing position. If the emission we have observed originates from this position, the flux scales in Fig. 11 should be increased by 7 per cent.

In Fig. 12 we have compared our integrated spectra with those of Sullivan (1973). The velocities of the two main features at +0.5 and +3 to +4 cm/s have remained stable over the 6-yr interval, but between 1969–70 and 1976–77, the total integrated flux in the velocity interval −7 to +7 km/s has fallen by a factor of ~3.

S140

S140 is an H II region associated with the radio complex G106.7+5.3. Water vapour emission was detected by White & Little (1975), and found to lie close to a bright infrared source detected by Blair *et al.* (1975). Further observations have been reported by Morris & Knapp (1976) and Knapp & Morris (1976).

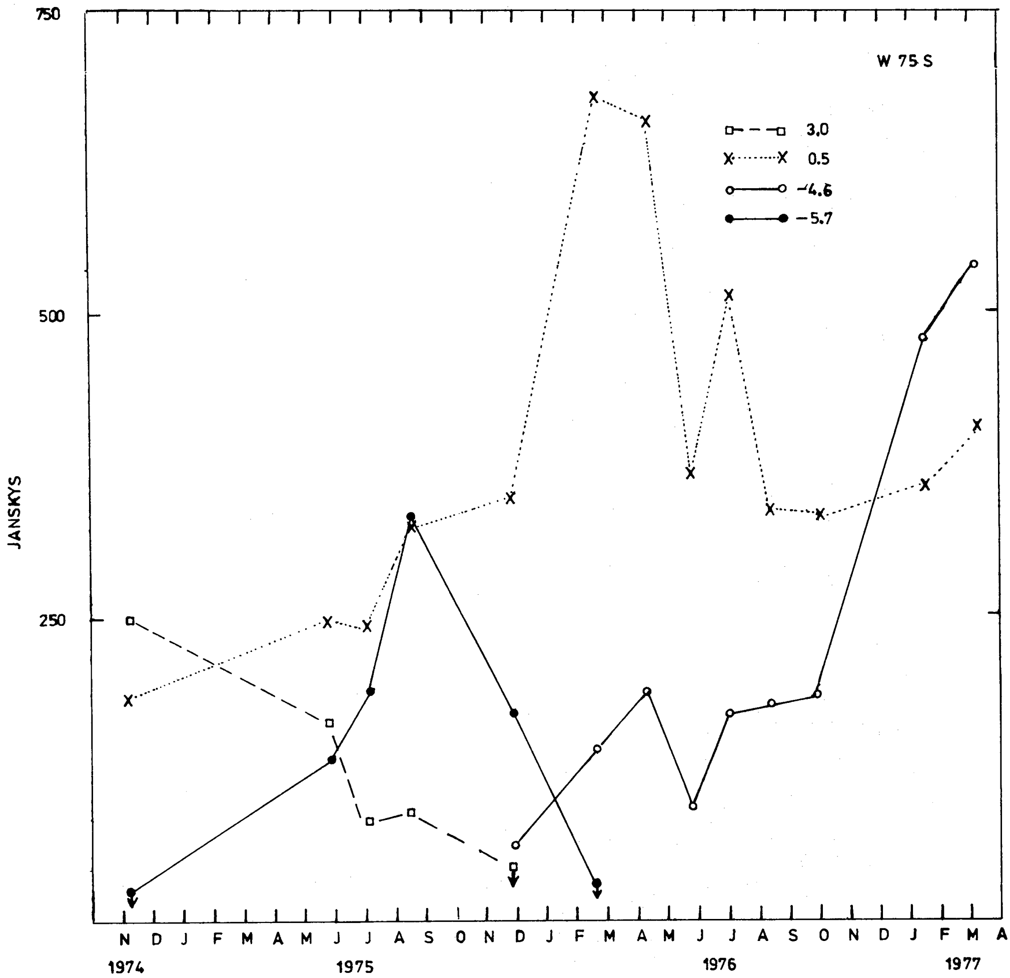


Figure 11. Intensity variations of the four strongest components in W75S.

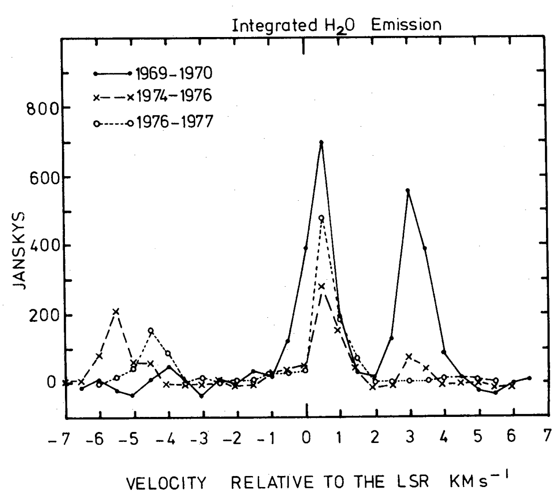


Figure 12. A comparison of the average spectra over the periods 1974–76 and 1976–77 with that of Sullivan (1973) over the period 1969 April–1970 March for W75S.

Spectra obtained for this source show three features, at velocities of −16, −15 and +10 km/s. Whereas those at −16 and −15 km/s remained constant during the monitoring period, the +10 km/s component reached a peak of 500 Jy in 1975 May and had decayed to less than 100 Jy by 1975 October, subsequently remaining below this level. The corre-

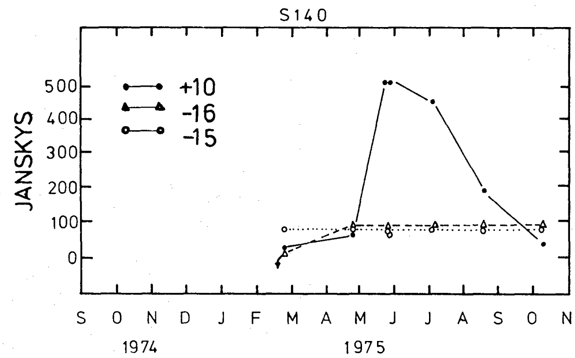


Figure 13. Intensity variations of the three components in S140.

sponding *e*-folding times for this variation were <2.6 and $\sim 8\times10^6$ s for the rise and fall respectively. The time variation in the three components is displayed in Fig. 13.

Observations made at a grid of points at half beamwidth intervals show that the two weaker components lie within 15 arcsec of the +10 km/s component.

S152

This weak H_2O maser source was detected by Lo & Burke (1973). During the period of our observations only one positive detection of this weak source was obtained. The spectrum shows a component of ~ 50 Jy intensity at a radial velocity of −51 km/s.

NGC 7538

This bright optical nebula has a complex radio structure with diffuse thermal emission over most of the source, and a compact H II region at the southern tip (Habing, Israel & de Jong 1972; Israel, Habing & de Jong 1973).

An H_2O maser source was discovered by Johnston *et al.* (1973) close to an OH maser site. Further observations by Cato *et al.* (1976) and Genzel & Downes (1976) led to the discovery of a second H_2O maser source lying 1.5 arcmin north and coincident with the compact H II region. We made observations at a grid of points in 1975 February in an attempt to determine the position of the maser site. Our position for all spectral components was in agreement with that of Johnston *et al.* and we did not at that time detect any emission from the compact H II region. Further observations made in 1976 October clearly showed the presence of a bright (~ 300 Jy) spectral component with a radial velocity of −61 km/s at the position of the compact H II region. The sudden appearance of this new maser has been noted by Genzel & Downes (1976). The spectra shown in Fig. 14 result primarily from emission from the southern source, although they may be contaminated at −61 km/s by the northern source.

3 Analysis

The present data contain information on the time variations of a large number of water maser components in 14 sources associated with H II regions. In analysing these data, great care must be exercised to exclude those components which represent the blending of several features which may be varying independently. The severity of this problem can be assessed from *VLBI* maps of water maser sources in which individual velocity components are separated spatially. Accordingly, a sample of 77 low-velocity components were selected

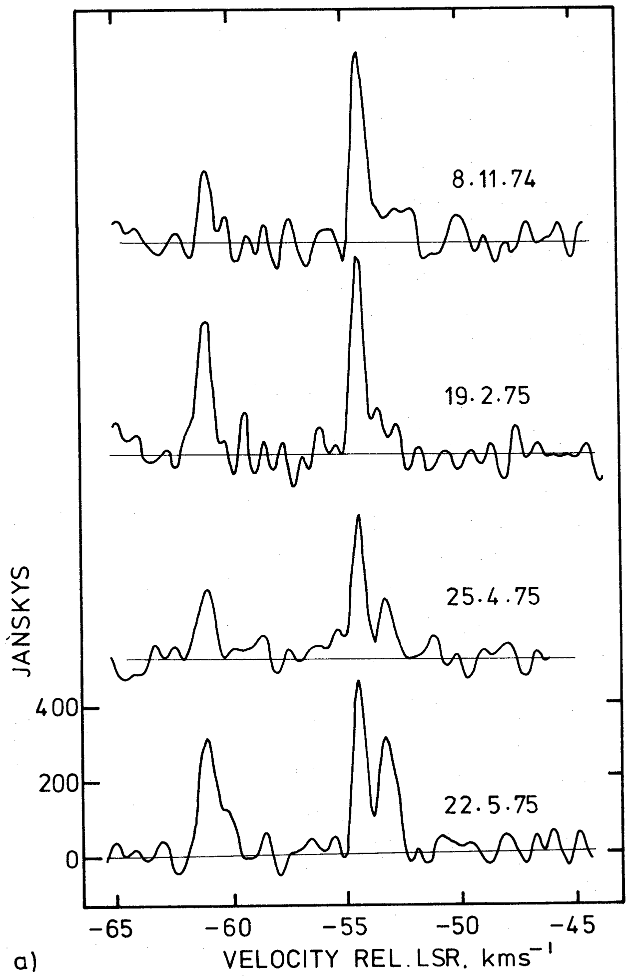


Figure 14. (a) and (b). Spectra of NGC 7538 with velocity resolution 0.4 km/s at $\alpha(1950) = 23^{h}\,11^{m}\,36^{s}$, $\delta(1950) = 60°\,10'\,20''$. There may be some contamination at −61 km/s from the maser source 1.5 arcmin north of this position discovered by Genzel & Downes (1976).

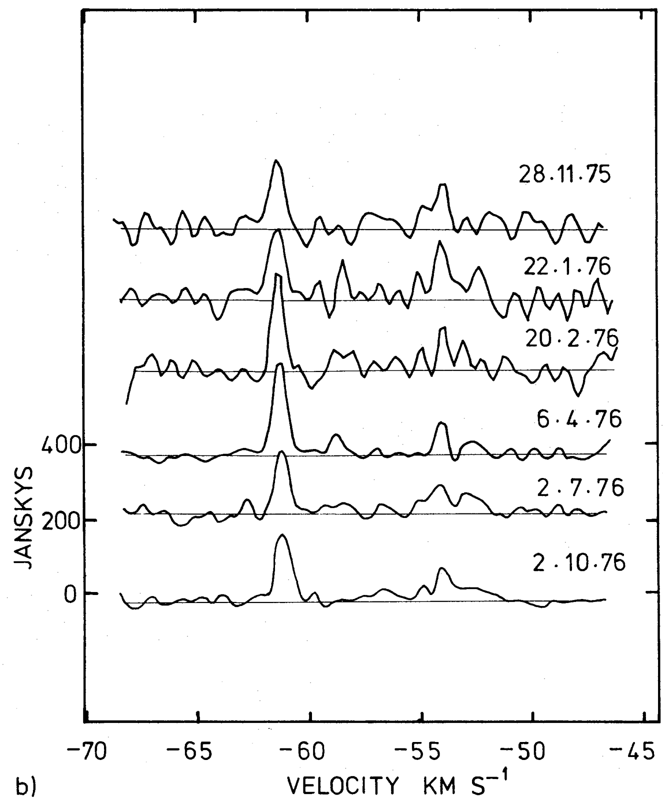
from the *VLBI* maps of W3, W3OH, Orion A and W49N presented by Genzel *et al.* (1978). Roughly one-half of these components lay within 1.0 km/s of a neighbouring component and ~ 15 per cent of the sample had an adjacent feature within 0.5 km/s. It is evident from these results that intensity measurements of low-velocity components in complex sources are likely to be subject to considerable uncertainty when the velocity resolution is > 1 km/s.

In order to minimize the uncertainties due to blending the following selection criteria were applied to the data:

(a) FWHM < 1.5 km/s and exhibiting no asymmetry at a level above 25 per cent of the peak flux of the component;

(b) in complex spectra (e.g. ON1, ON2, W75S) only the components more than 0.8 km/s from an adjacent component > 40 per cent as strong were included.

On applying these criteria to the data sufficient samples remain for only two sources (W3 and ON1) to be analysed individually. The samples remaining for all other sources must be considered together for meaningful statistics to be obtained.



3.1 SHORT-TERM VARIABILITY IN W3 AND ON1

Time variations in components with velocities −42, −40.8, −39.4, −35.6 and −33.8 km/s in W3 and 9.2, 10.1, 11, 13.6 and 16 km/s in ON1 were analysed as follows. If the flux of a source on the nth observing run was S_n a set of samples

$$X_n = \left(\frac{S_n}{S_{n-1}} - 1\right) \times 100 \quad \text{if } S_n > S_{n-1}$$

or

$$X_n = \left(\frac{S_{n-1}}{S_n} - 1\right) \times 100 \quad \text{if } S_n < S_{n-1}$$

was calculated for all n and all features. A histogram showing the distribution of X_n was then

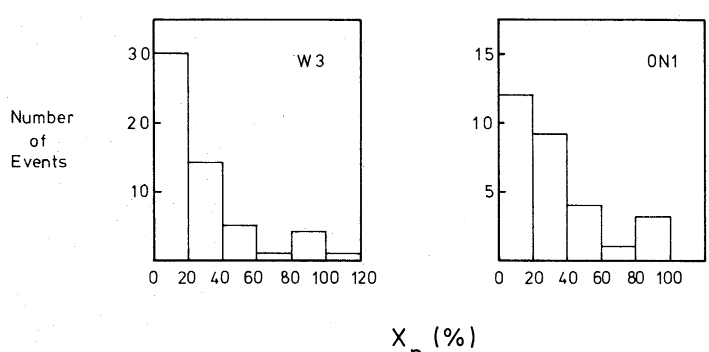


Figure 15. Histograms showing rates of variability in W3 and ON1.

plotted (Fig. 15), where the mean interval between observing runs was 46 ± 4 day ($\sim 4 \times 10^6$ s). No variations in any component between runs > 120 per cent were detected in these two sources. This behaviour is similar to that found in Orion A but contrasts with that in W49N where variations up to 400 per cent were observed (Little *et al.* 1977).

3.2 SHORT-TERM VARIABILITY IN THE WHOLE SAMPLE

After application of the selection criteria, data remained on 51 maser components in W3, S255, S269, W31, W33, ON1, ON2, CRL2591, W75S, S140 and NGC 7538. A composite histogram was constructed from this data combined with that from Little *et al.* (1977) on Orion A and W49N (Fig. 16(a)). In Fig. 16(b) the data contributed by W49N have been removed: it can be seen that large flux variations ($X_n > 100$ per cent) are characteristic of sources other than W49N although the largest variations are found in this source which showed changes $X_n > 100$ per cent in ~ 25 per cent of samples. Of the remaining sources ~ 75 per cent of samples had $X_n \leqslant 50$ per cent and ~ 90 per cent had $X_n \leqslant 100$ per cent.

3.3 LONG-TERM VARIABILITY

The present data taken during 1974–75 and 1975–76 can be compared with that obtained by Sullivan (1973) during 1969–70 for the sources W3, ON1 and W75S. Averaged spectra for these sources over these two periods have been presented in Figs 2, 8 and 12. The integrated flux from the averaged spectra of 1969–70 and 1975–76 have been derived and combined with the equivalent data from Little *et al.* (1977) for W3(OH), Orion A, W49N and W51M in Table 2.

Sullivan's pointing position for ON1 lies ~ 100 arcsec from our pointing position given in Table 1 which is the same as that observed by Genzel & Downes (1977). Assuming that all these observations are of the same maser source, the 1969–70 integrated flux should be revised to 4.5×10^3 Jy km/s yielding a (1975–76):(1969–70) integrated flux ratio of 0.24. Further high sensitivity observations at Sullivan's position are required to confirm that only

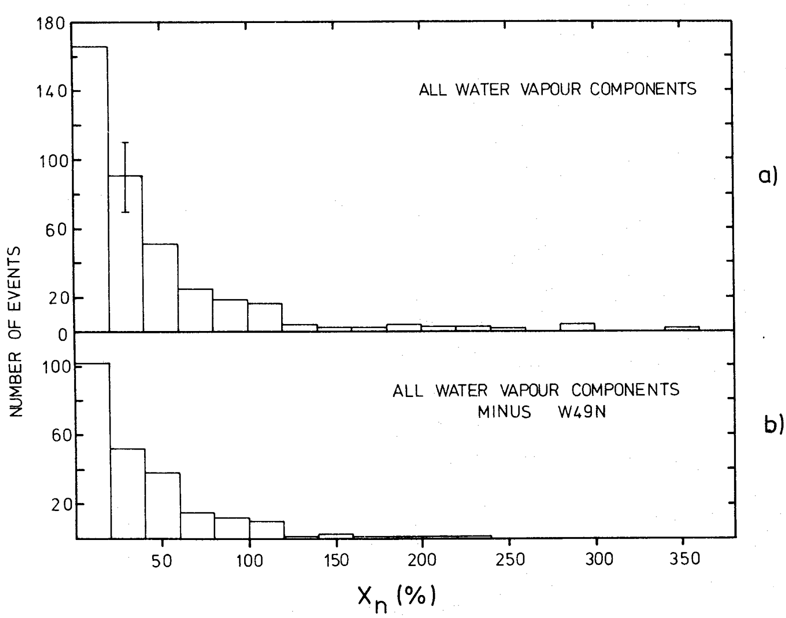


Figure 16. (a) Histograms showing rates of variability in all water maser sources in present sample plus Orion A and W49N. (b) as (a) but without data on W49N.

Table 2. A comparison of the average integrated flux of W3, W3(OH), Orion A, W49N, W51M, ON1 and W75S during 1975–76 with Sullivan's data of 1969–70.

Source	Velocity range (km/s)	Integrated flux 1969–70 (Jy km/s)	Integrated flux 1975–76 (Jy km/s)	Ratio of integrated flux (1975–76) : (1969–70)
W3	$-45 \rightarrow -30$	2.5×10^3	1.2×10^3	0.48
W3(OH)	$-55 \rightarrow -45$	1.2×10^4	1.2×10^4	1.0
Orion A	$-9 \rightarrow 20$	6.1×10^4	8.1×10^4	1.33
W49N	$-15 \rightarrow 30$	2.3×10^5	1.3×10^5	0.57
W51M	$52 \rightarrow 72$	1.5×10^4	3.5×10^4	2.33
ON1	$5 \rightarrow 22$	1.1×10^3	1.1×10^3	1.0
W75S	$-6.5 \rightarrow 6.5$	1.3×10^3	4.7×10^2	0.36

one water maser source is present in ON1. ON1 apart, it is apparent from Table 2 that significant long-term time variations are found in W3, W49N, W51M and W75S. Sullivan (1973) quotes the *relative* accuracy of his flux density measurements as ± 15 per cent, whilst the relative accuracy of our measurements is believed to be similar (Little *et al.* 1977). The large changes seen are therefore real and greater than possible errors in absolute flux density calibration since some sources show an increase (Orion A, W51M) and some a decrease (W3, W49N, W75S) in integrated flux.

Long-term time variations imply that the source of excitation is common to many maser components. Little *et al.* (1977) have discussed the implications of these variations for models of W51M and W49N. They conclude that the flux of radiation from the common object must vary in a time-scale of ~ 10 or < 100 yr, depending on whether the masers are saturated or unsaturated. Recently, however, *VLBI* observations (Genzel *et al.* 1978) have shown that at least 10 separate centres of activity exist in W49N. If each of these centres indicates the site of a young stellar object responsible for pumping the nearby maser components, it is surprising that systematic long-term variability should be detected. From the data of Little *et al.* (1977) it appears that only the low-velocity components have varied significantly, the high-velocity blends remaining at a similar level as during 1969–70. Inspection of the *VLBI* map of Genzel *et al.* (1978) shows that most of the integrated low-velocity flux in W49N is emitted by four of the 10 centres of activity. It is therefore plausible that the observed long-term variations are due to changes in one or more of these centres of activity. This conclusion is strongly supported by the recent detection of correlated short-term variability in one of these centres in W49N (White 1979).

VLBI maps of W51M (Genzel *et al.* 1978; Walker *et al.* 1978) show that in this source most of the emission arises from a single centre of activity. Changes in the pump rate of the central object would readily account for the long-term variations observed.

3.4 RELATED VARIABILITY IN FEATURES OF SIMILAR VELOCITY

We have examined the present data for evidence of related variability in features of similar velocity such as that noted by Little *et al.* (1977) in W49N where the high velocity features at −84 and −82 km/s peaked within six weeks of each other. This behaviour has been observed by Genzel & Downes (1977) in the low-velocity emission from several sources (W51M, W75N, W75S(3), 10.5 + 0.0) which from their double-peaked spectra they believe to be shell sources. They interpret these related variations in terms of a saturated travelling-wave maser with several modes and suggest the designation of 'mode switching' to the phenomenon. Only one source in our present sample shows evidence of this form of variability. The features at −4.6 and −5.7 km/s in W75S interchanged intensity between

1975 November and 1976 February. Genzel & Downes's source designated W75S(3) is a different H_2O maser lying 3.3 arcmin north of our pointing position. Interferometric observations are required to determine whether these components are physically related. The variability could be explained by a change in the intensity ratio between the $F = 7–6$ and $F = 5–4$ hyperfine components. It is then puzzling that the $F = 6–5$ hyperfine component is not also seen, but observations of the hyperfine structure (Moran *et al.* 1973; Cato *et al.* 1976) have shown that they are often present in non-equilibrium ratios. Genzel & Downes (1977) reject this hypothesis to explain their observations of related variability in features having similar velocity due to lack of consistent agreement between the hyperfine intervals and the observed velocity separations and propose that the splitting is determined by the kinematics of circumstellar shells. If the pump radiation is beamed and the direction of the beam varies, perhaps due to movement in an obscuring dust cloud between the pump source and the masing regions, then different clouds of water vapour may be successively excited.

4 Discussion

The time-dependent equations of radiative transfer for a maser region larger than it is wide have been solved recently by Salem & Middleton (1978). They find that there is no inherent feature in these non-linear equations which leads to variations in the output of the maser provided that physical conditions such as the number density and pump rate remain constant. It follows that the observed time variations in astrophysical masers must be due to changes in pump rate or source geometry or possibly a combination of both.

The response to a sudden increase in pump input is different in saturated and unsaturated masers. In a saturated maser, the output varies quasi-periodically with a period equal to the light-travel time along the length of the maser. The oscillations are due to the reduction in the inversion along part of the maser by the amplified forward wave causing a drop in intensity until the inversion is restored by the pump. If the maser is unsaturated, the intensity will increase monotonically to the new equilibrium value. If the pump input varies sinusoidally then the maser output is modulated similarly but no resonant behaviour is found if the pump rate frequency is harmonically related to the natural frequency of oscillation of the maser. A further type of behaviour is found in a 'pre-pumped' maser where significant population inversion is achieved before other conditions for amplification are satisfied. The intensity in this case rises sharply to a peak value before falling to the steady-state value which may be much lower.

Changes in source geometry can give rise to an effective change in pump rate where the pump radiation is beamed, for example by changes in opacity in an obscuring dust cloud moving between the pump source and maser volumes. Alternatively, relative movement of water vapour clouds can give rise to favourable velocity alignments such that the effective length of the maser region is enhanced for an interval of time.

Several pumping schemes have been proposed for the water maser sources. These include the shock front excited, radiative pump model of Litvak (1969), the collisional pump model of de Jong (1973), the selective predissociation by ultraviolet absorption model of Oka (1973) and the hot-dust-cool-gas model of Goldreich & Kwan (1974). Several authors have discussed the relative merits of these pumping schemes (Heckman & Sullivan 1976; Morris 1976; Genzel & Downes 1977; Little *et al.* 1977; Cook 1977, 1978) but none is found to satisfy completely the constraints imposed by the present observational data.

Litvak's mechanism cannot supply sufficient pump power for maser sources with photon emission rates $> 10^{45}\,s^{-1}$ (Goldreich & Kwan 1974). The most powerful H_2O maser sources have photon emission rates $\sim 10^{48}\,\mathrm{s}^{-1}$ but this figure would be reduced if the radiation was anisotropic. The collisional pump model of de Jong can provide more pump power but predicts dimensions of the maser regions which are several orders of magnitude larger than those observed. The hot-dust-cool-gas model of Goldreich & Kwan predicts levels of infrared radiation from the hot dust significantly greater than observed. A further problem with this model is that the high rates of variability observed are difficult to explain. The time-scale for thermalization between the dust and gas assuming $n_{H_2} = 10^9\,\mathrm{cm}^{-3}$, for example is $\sim 7 \times 10^6$ s, significantly greater than the *e*-folding time detected in NGC 1333 of 3×10^5 s. Higher rates of variability demand either higher values of n_{H_2} or some more rapid form of thermalization. Oka's mechanism of selective predissociation by absorption of ultraviolet radiation is particularly attractive for water masers in the vicinity of H II regions but an important feature of this model is the presence of OH more than 10 times more abundant than H_2O. There is some doubt that the OH can exist in the strong ultraviolet radiation field necessary selectively to dissociate the H_2O.

Cochran & Ostriker (1977) have shown that, for newly formed massive O stars, radiation pressure would drive dust grains into the accreting gas. The high gas density of 10^8–$10^9\,\mathrm{cm}^{-3}$ within 10^{15}–10^{16} cm of the stellar surface could provide several optical depths of absorption between the star and maser regions lying $> 10^{16}$ cm distant. The problem of excess infrared radiation in the Goldreich & Kwan (1974) pumping model could thereby be overcome and the movement of density inhomogeneities in the stellar wind would provide a natural means of rapidly varying the pump power to the maser regions.

5 Conclusions

The observations of time variations in 14 water maser sources over a period of 32 months has confirmed the wide range of time-scales from several days to several years. Although time-varying solutions of the equations of radiative transfer for an astrophysical maser have been found and several detailed pumping schemes proposed, there is an urgent need for a theory of some elementary time-varying masers with defined geometrical and physical properties. An adequate theory to explain the complex behaviour observed will need to combine these parameters with the dynamics of the maser regions in the vicinity of an early-type stellar object.

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