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LONG TERM VARIABILITY OF SOUTHERN HEMISPHERE WATER MASERS

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RESUMO-NOTAS/ABSTRACT-NOTES

The intensities of several water vapor masers in the direction of HII regions were monitored, almost on a monthly basis, from December 1980 to December 1986. The spectral shape of all sources changed in time with the fluxes of individual velocity components varying on timescales of 10^6 to 10^7 sec. We discuss the evolutionary stage and the dynamics of three of the monitored sources: G331.5-0.1, GGD25 (NGC6334C) and Orion A.

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OBSERVAÇÕES/REMARKS

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Abstract

The intensities of several water vapor masers in the direction of HII regions were monitored, almost on a monthly basis, from December 1980 to December 1986. The spectral shape of all sources changed in time with the fluxes of individual velocity components varying on timescales of 10^6 to 10^7 sec. We discuss the evolutionary stage and the dynamics of three of the monitored sources: G331.5-0.1, GGD25 (NGC6334C) and Orion A.

1- INTRODUCTION

The temporal variability of 22 GHz water masers associated with regions of star formation has been studied by several authors (Sullivan 1971, 1973; White and MacDonald 1980; Little et al. 1977; Lekht et al. 1982).

The variations of individual sources have also been analyzed: W49N (Gammon 1976; White 1979), W3(OH) (Haschick et al. 1977; Burke et al. 1978), W51 Main (Genzel and Downes 1977b, 1979), the Orion flare (Matveenko et al. 1980; Abraham et al. 1981, 1986), Cepheus A (Mattila et al. 1985; Rowland and Cohen 1986) and G305.8-0.2 (Vilas Boas et al. 1990). These works have shown that these masers vary on timescales from 10^4 to 10^7 sec.

In this paper, we present the results of the monitoring of the following sources: G331.5-0.1, GGD25 (NGC6334C) and Orion A. They were observed almost in a monthly basis, from December 1980-86 (Table 1). During this period all sources varied on time scales of 10^6 to 10^7 sec.

2- EQUIPMENT AND METHOD OF OBSERVATION

All observations were made at Itapetinga Radio Observatory(*), with the 13.7 m telescope, which has a pointing accuracy of 20". We used a room temperature mixer receiver with system temperature of 900 K (SSB), and a 46-channel filter spectrometer with 100 kHz resolution. At the water vapor frequency, the velocity resolution is 1.35 km s^{-1} over a range of 62.1 km s^{-1}.

The observations were made using the beam-switching ON-ON technique with two rectangular horns separated horizontally by 20' in the Cassegrain focus. At 22 GHz the HPBW of the horns is 4.1'. Each observation lasted for 20 min and the minimum detectable temperature was 1 K. We used Virgo A as prime calibrator which gave a conversion factor between flux density and corrected antenna temperature of 45 Jy/K, and an aperture efficiency of 42%. The calibration of the data was made with a reference noise source (110 K), whose stability is better than 1%.

The antenna temperature of each source was corrected for the optical depth, whose value varies from 0.15 to 0.50 during the year. The data were also corrected for the variation of antenna gain with elevation and for radome transmission (Kaufmann et al. 1977).

(*) operated by CRAAE - INPE, USP, Mackenzie and UNICAMP.

3- DESCRIPTION OF SOURCES AND RESULTS

3.1- G331.5-0.1

G331.5-0.1 is in the Norma region at a distance of 6.5 kpc and belongs to a large HII region complex. Its radio continuum emission is thermal. The water maser is 3' S of the continuum peaks at 408 MHz (Shaver and Goss 1970), 2.3 GHz (Jonas et al. 1985) and 5 GHz (Goss and Shaver 1970). Molecular lines of H_2CO (Gardner and Whiteoak 1984), CO (Gillespie et al. 1977), HCN (Whiteoak and Gardner 1978), CS (Gardner and Whiteoak 1978), HCO^+ (Batchelor et al. 1981), NH_3 (Scalise et al. 1981), and maser lines of OH (Knowles et al. 1976) and H_2O (Knowles et al. 1978) were detected at velocities close to the velocity of the H109α recombination line (Wilson et al. 1970). Nevertheless, no compact HII region has been detected in this complex (Habing and Israel 1979).

Epchtein and Lépine (1981) found a bright infrared object localized between the OH/H_2O maser complex and the centre of the HII regions but not coinciding with these sources. Assuming that the IR object emits like a black body, they found the luminosity to be 1.5×10^4 L_o. The color indices found were H-K = 1.8, K-L = 4.72 and L = 5.98 which correspond to a steep spectrum in the near IR with T_{K-L} = 500 K.

Moorwood and Salinari (1981) detected four IR objects at 3.6 μm in this region. The first source (IRS1) was found to be outside the error circles where OH and H_2O were found, but within the 3σ . This source is supposed to be associated with a very young pre main-sequence object. The second source, IRS2, is weaker than IRS1, looks like a compact object at 10 μm but was not detected at 2.2 μm. Its position coincides with the OH and H_2O positions. At 9.7 μm it has one of the highest opacities detected to date, of the order of 10. This component can be attributed to the presence of cold dust in front of an optically thin source dominated by hot silicate grains. The luminosity found in the 2-20 μm range for IRS2 is 40 times stronger than that of IRS1, but in the 40-300 μm range it was found to be the same for both objects (Moorwood and Salinari 1983). Their conclusion is that this source is one of the youngest objects ever observed because no ionized gas was detected in their hydrogen recombination line observations of Brγ (2.17 μm) and Pfγ (3.14 μm). The IR objects IRS3 and IRS4 are probably field stars due to their small K-L value.

In the period that this source was monitored, the H_2O maser at -95.9 km s^{-1} varied from 1100 Jy to 7200 Jy, with a maximum on March 1982. "The event" had a rise time of ~ 6 months, starting on September 1981. It remained in a quiescent state of 2500 Jy from July 1982 through early 1983. This flux implies a pumping energy of $(4\pi/\Omega)x3.6x10^{31}$ erg s^{-1} ($(4\pi/\Omega)x2.5x10^{47}$ photons s^{-1}) for the peak luminosity. For an isotropical spherical maser $\Omega = 4\pi$ whereas for a cylindrical maser $\Omega = 10^{-4}$. For an isotropic maser the total energy released would be $6x10^{38}$ erg s^{-1}.

Fig. 1 (a-r) shows the variation of the H_2O maser spectrum of G331.5-0.1 for December 1980-86. Fig. 2(a-d) shows the variation of the -95.9 km s^{-1} and adjacent velocity components (in corrected antenna temperature). Each observation is indicated by a cross joined by straight lines only for better visualization.

In Fig. 3 we tried to adjust the peak values of the -95.9 km s^{-1} feature over a two year period starting on August 1981 to the curve of the diffusion model by Burke et al. (1978). This model assumes an instantaneous burst of energy from a protostar embedded in a spherical cloud of gas and dust. Our data show that the intensity variation does not fit the diffusion model because the flux falls too fast.

Fig. 3 suggests that during the decay phase, the medium cooled rapidly, implying that the diffusion model was no longer the most adequate cooling mechanism or that there might be a superposition of several sources with individual diffusion curves. There may be other components with velocities closer to -95.9 km s^{-1}, which were not seen due to our poor spectral resolution of 1.35 km s^{-1} so that we can not specify the peak flux density nor the line width. It is possible that the temporal curve obtained could be the superposition of several individual components present in the region evolving with time.

The maser spots (~ 10^{13} cm) occur in the so-called active centers (~ 10^{16} cm) which are expanding disk shells surrounding the exciting massive star (Genzel and Downes 1977b; Reid and Moran 1981). Several active centers can be found in a region with a radius of ~ 10^{17} cm. From the observed time scale we can infer that the physical size of the region should be ~ 4.9×10^{17} cm. The diffusion curve may be applicable when we are dealing only with one maser component as observed in W3(OH) by Haschick et al. (1977) and Burke et al. (1978) and in Cepheus A by Mattila et al. (1985).

In Table 2 we present the computed values for the rise time, flux density and luminosity at the maximum and total energy of these four sources. We can see that the total energy of the event that occurred in G331.5-0.1 at -95.9 km s^{-1} is at least three orders of magnitude larger than the explosions that happened in the other three H_2O maser sources.

Two secondary peaks were observed (crosses in Fig. 3) in the temporal curve of G331.5-0.1, one on March 6, and the other on September 11, 1982. It is interesting to note that a similar behaviour in the decay phase of H_2O maser explosions, i.e., the presence of secondary peaks some time after the main event were observed by other authors. Burke et al. (1978) thought the secondary peak was due to observational errors in their data on W3(OH). For Cepheus A, Mattila et al. (1985) suggested that the three secondary maxima could be due to periodic fluctuations, because they happened within a 13 day period. Other interpretation is that the peaks were originated in independent maser spots, excited by an unique source. If we assume that the pump is radiative, one can compute the distance between the two maser components as $\sim 4.9 \times 10^{17}$ cm, the same as the physical size of the region, obtained from the observed rise time. Another interpretation is that the energy stored in the magnetic field of the region (Deguchi and Watson, 1986) produces the secondary peaks. In spite of the lack of VLBI maps of this region, and even with the poor resolution of our spectrometer, it looks rather complex, showing many spectral components.

If the diameter of each maser spot is $\sim 7 \times 10^{13}$ cm, the brightness temperature at the peak flux of this source was 2.8×10^{11} K. Assuming that this maser was not saturated and the input brightness temperature was 50 K (Goldreich and Keeley, 1972), the optical depth should be 22.4, which indicates that the region is optically thick at the observed water maser line frequency.

3.2- GGD25 (NGC6334C)

NGC6334 is a complex HII region associated with an elongated (10 x 3 pc) molecular cloud which covers more than 30 arcmin along the galactic plane and is at a distance of 1.7 kpc (Neckel 1978). Observations of molecular lines like H_2CO (Gardner and Whiteoak 1984), HCN (Whiteoak and Gardner 1978), CS (Gardner and Whiteoak 1978), HCO+ (Batchelor et al.1981) and NH_3 (Rodriguez et al. 1980) did show their velocities close to the velocity of the recombination lines H66α (Georgelin and Georgelin 1970) and H109α (Wilson et al. 1970) indicating the presence of a molecular cloud associated with the complex. Radio and IR observations of this region indicated the presence of at least ten compact sources (Reid and Moran, 1981) as well as indicators of stellar formation like OH masers (Raimond and Eliasson, 1969), H_2O masers (Moran and Rodriguez, 1980), near IR sources (Becklin and Neugbauer, 1974), hot CO spots (Dickel et al., 1977), continuum peaks at 1 mm (Cheung et al., 1978) and peaks in the distant IR (Mc Breen et al., 1979).

Five water vapor masers were found in the molecular cloud NGC6334 by Moran and Rodriguez (1980). Among them, GGD25 (NGC6334C) is a peculiar object due to its large blueshift, of -80 km s^{-1}, quite different from the velocity of the four other masers found in this region whose velocities lie within 10 km s^{-1} of the cloud velocities and also because it is two orders of magnitude more luminous than the other masers. Assuming the emission from GGD25 to be isotropic, we obtain a luminosity larger than 10^{30} erg s^{-1}. This high luminosity has been observed only in masers associated with the formation of OB stars (Genzel and Downes 1977b).

Braz and Epchtein (1982) found a weak but very red source coinciding with the position of the H_2O maser, as determinsioed by Moran and Rodriguez (1980). The IR color indices observed were quite high with J-K = 3.28, H-K = 2.18, K-L = 4.12 and L = 8.90.

Moran and Rodriguez (1980) proposed an evolutionary sequence for the five masers of the region where GGD25 is assumed to be the most evolved one. Near its position there are IR peaks, CO hot spots, HII continuum peak, but no OH maser was found. As there are only two OH masers associated with the five H_2O masers, the evolution phase of OH should be shorter than that of the water. The VLBI results obtained by Rodriguez et al. (1980), for this Herbig-Haro type object, showed a multispot H_2O maser with all components restricted to a region of 5 m.a.s., or 10^{14} cm, at the distance of 1.7 kpc (Rodriguez et al. 1978).

Our results show that several water maser velocity components present variations in their intensities (Fig. 4 a-r), some with large variations (Fig. 5 a-o) although no explosion happened during the period of the observations.

Strelnitskii and Syunyaev (1973) showed that the high velocity water masers can be explained in terms of blobs being accelerated by the stellar wind. This strongly suggests that the water maser clouds mmy be no longer collapsing towards the star but just starting to expand. In the model of "interstellar bullets" (Norman and Silk 1979) a young pre main-sequence star (pre-T Tauri) develops a strong wind or radiation pressure, which interacts with the material of the original cloud. This phenomenon could explain the origin of HH-type objects as well as the associated water vapor masers.

The time variability in intensity of the several maser components here observed are apparently correlated (Fig. 4). This could be explained as due to instabilities of a common exciting source, probably a pre-main sequence star with a strong stellar wind.

3.3- ORION A

The water masers, along with the high resolution IR data, indicate that there are three different maser components in the Orion-KL region: the shells, the low velocities and the high velocities (Genzel and Downes 1977a; Genzel et al. 1981).

The shell components of the water maser, with an expansion velocity of 18 km s^{-1}, are placed 10^{15} - 10^{16} cm from IRc2. Most of these components did not present significant changes in radial velocity or intensity in the last years (Sullivan 1973, Matveenko 1981, Abraham et al. 1986). Deguchi (1977) suggested that these components could be radiatively pumped through the vibrational states of the water molecule.

The low velocity masers in the Orion KL region also have very stable radial velocities and a lifetime of more than ten years (Genzel et al. 1981). The temporal variability in intensity, and particularly, the flux density increase of three orders of magnitude for the 8 km s^{-1} component (Abraham et al. 1981, 1986) may indicate that these masers are not irradiating isotropically.

The flux density of a cylindrical saturated maser with length l, pumping rate P is proportional to Pl^3. In order to explain the increase of this maser feature in Orion, it was necessary that the pumping ratio in the region had changed three orders of magnitude or that the length of the cylinder had increased by one order of magnitude.

Based in the observational results obtained with the Crimea-Puschino interferometer, Matveenko (1981) suggested the existence of several sources with sizes smaller than 0.2 AU. Using the radio interferometers Crimea-Effesberg and Green Bank-Haystack, Matveenko et al. (1982) suggested the existence of a disk shaped compact source with a radius of 0.25 AU surrounded by a halo with 3 AU in diameter. These results show that the emission of the explosion originated in a compact nucleus with 0.5 m.a.s. which was responsible for 65% of the flux and that the remaining emission came from a halo with 5 m.a.s. diameter. During the quiet periods the major part of the radiation arose in the halo and during the active periods from the disk.

The high velocity masers from Orion KL are extremely variable and the lifetime of each individual component is of the order of years. They are usually one or two orders of magnitude weaker than the low velocity components. Their apparent diameters, obtained through VLBI measurements, are smaller by a factor of 3 to 10 when compared with the low velocity spots (Genzel et al. 1981). The high velocity masers are probably collisionally pumped due to the deceleration in the vicinities of the molecular cloud.

The time variability of the 8 km s^{-1} component of the water maser spectrum of Orion has been studied elsewhere (Abraham et al. 1981, 1986, Matveenko et al. 1980, 1981, 1982, Vilas Boas and Abraham, 1988). Our objective was to observe the behaviour of the other velocity components during all the periods that the four explosions took place: October 1979, April 1980, October 1983 and November 1984, and try to verify which is the most likely pumping mechanism for the region.

The results of this monitoring are presented in Fig. 6 (a-r) and 7 (a-p), where we can see that many spectral components have significant changes, some varying faster than the others. None of the velocity components presented simultaneous variability correlated with the successive explosions that happened in the 8 km s^{-1} component. This suggests that this maser feature is placed in an isolated region.

4- CONCLUDING REMARKS

Among the several water masers associated with star forming regions, which we are monitoring almost monthly, we have selected for the present work the sources G331.5-0.1, GGD25 (NGC6334C) and Orion A and tried to analyze their behaviour from December 1980-86. The intensity variations occurred on timescales of 10^6 to 10^7 sec.

G331.5-0.1 showed only a slow, but significative, variation in intensity of the component at -96.0 km s^{-1}. This line rose from 1100 Jy to 7200 Jy in 188 days with a peak flux that implies a pumping energy, if the maser is isotropic, of 3.6×10^{31} erg s^{-1} (2.5×10^{47} photons s^{-1}) and a total energy of 10^{38} erg s^{-1}. The physical size of the maser was assumed to be 5×10^{17} cm. The collisional pumping mechanism proposed by Burke et al. (1978) gives a reasonable fit to the rise time and the beginning of the decay phase. The rapidity of the decay may rule out the diffusion model for this flare. Two secondary maxima were observed in the G331.5-0.1

temporal curve. One explanation is that the peaks were originated in independent maser spots excited by an unique source. The other is that the peaks were produced by the energy stored in the magnetic field of the region.

In GGD25, the high velocity of the water maser with respect to the molecular cloud and the time variations found in this maser could be associated with instabilities in the exciting source, probably a pre-T Tauri phase star.

Fast and slow time variability were found in Orion A, but it seems that these events are not at all correlated with the four major outbursts that happened at the velocity of 8.1 km s^{-1}, suggesting that this presently active maser spot is in an isolated region.

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Figure 1 (a-r) = Time variation of the water maser features in G331.5-0.1 from Dec.80 to Dec.86.

Figure 2 (a-d) - Time variation of the -95.9 km s-1 and adjacent features of the water maser in G331.5-0.1 from Dec.80 to Dec.86.

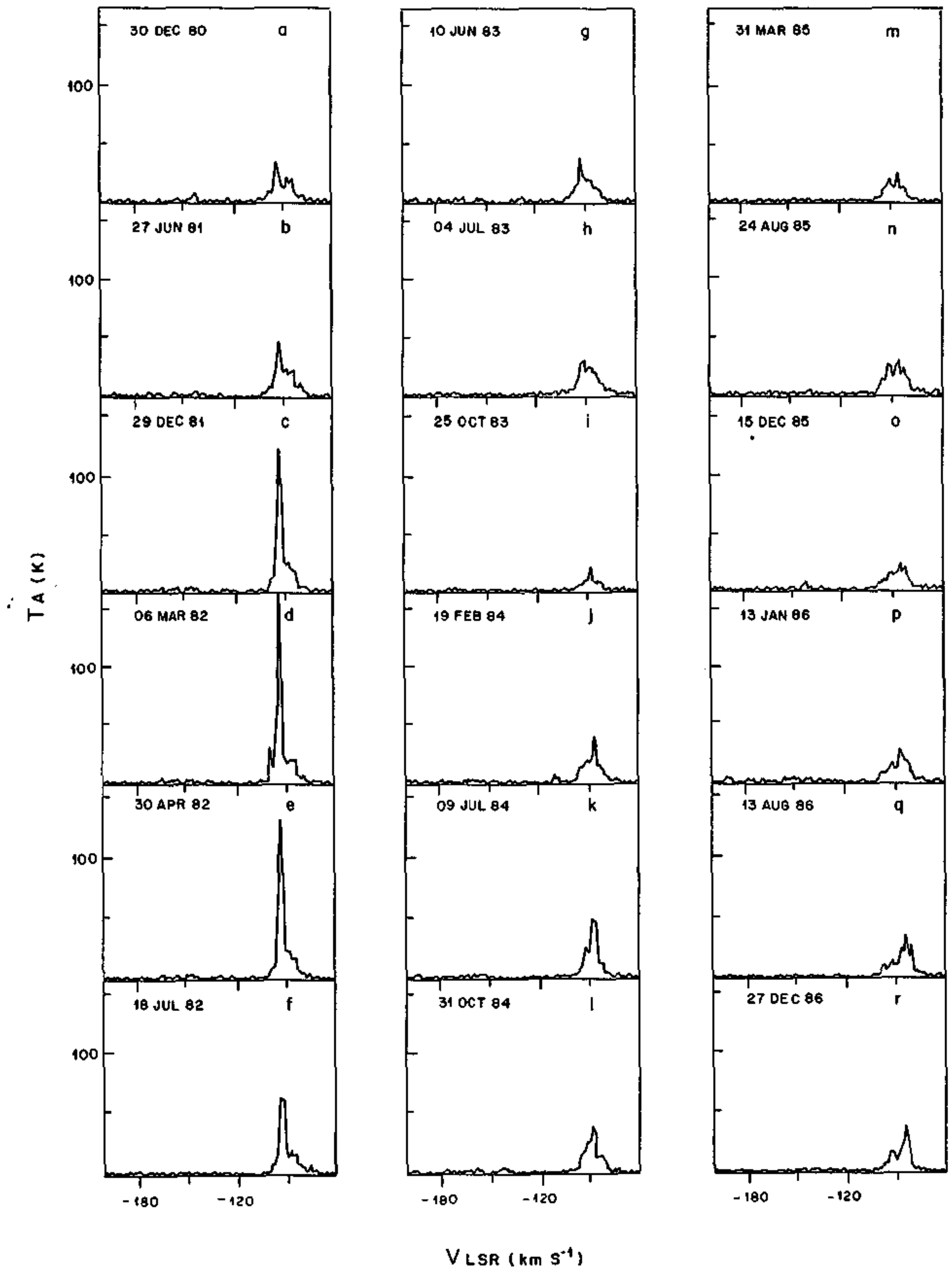
Figure 3 - Comparison of the diffusion model with the data obtained for the -95.9 km s-1 feature in G331.5-0.1. The points are the same as in Fig. 2a from Aug.3, 1981 to Jul.27, 1983.

Figure 4 (a-r) - Time variation of the water maser features in GGD25 from Jan.81 to Dec.86.

Figure 5 (a-o) - Time variation of the -75.9 km s-1 and adjacent features of the water maser in GGD25 from Jan.81 to Dec.86.

Figure 6 (a-r) - Time variation of the water maser features in OrionA from Dec.80 to Dec.86.

Figure 7 (a-p) - Time variation of the 0.7 km s-1 and adjacent features of the water maser in Orion A from Dec.80 to Dec.86.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09 JUL 84 k
31 OCT 84 l
31 MAR 85 m
24 AUG 85 n
15 DEC 85 o
13 JAN 86 p
13 AUG 86 q
27 DEC 86 r
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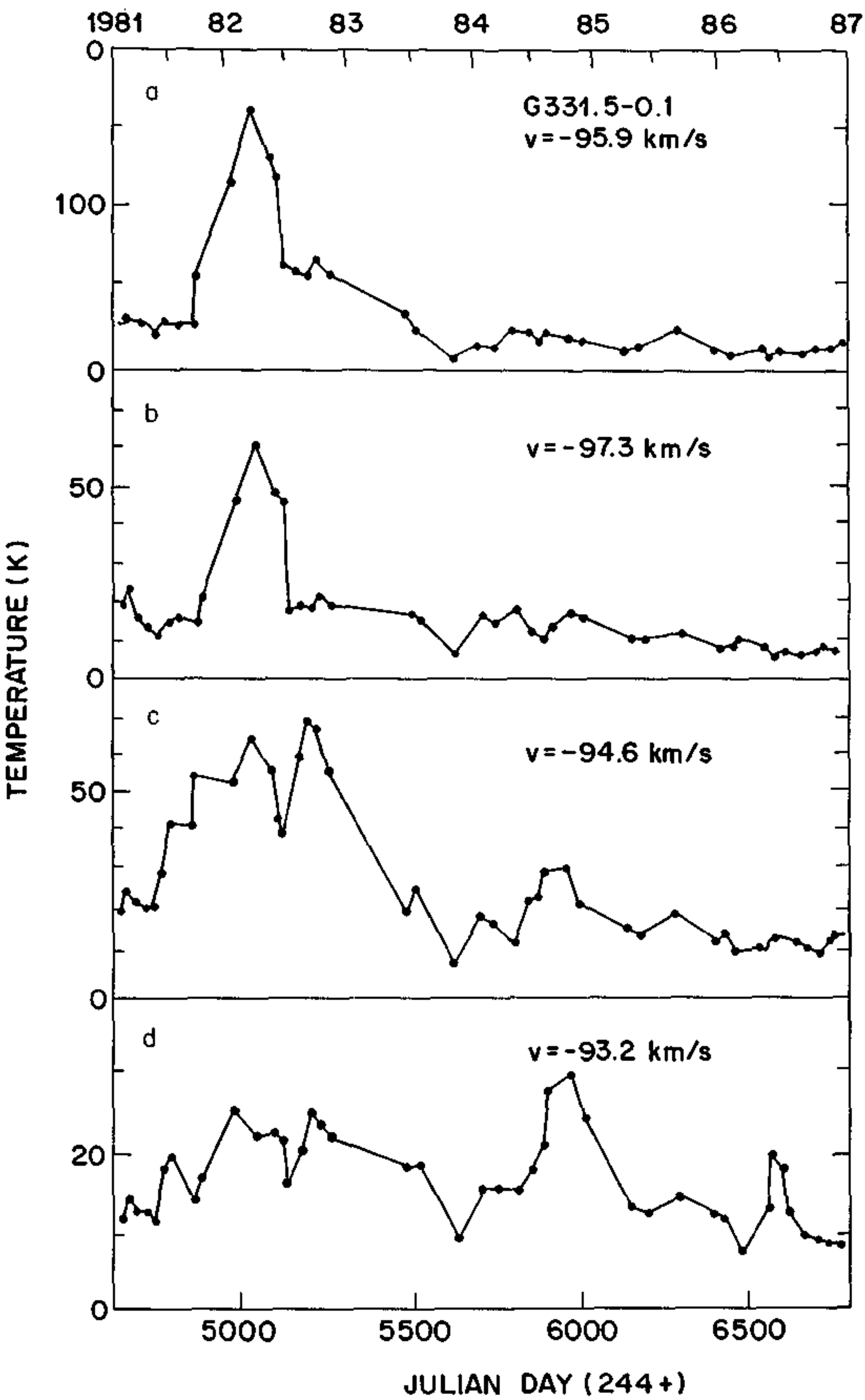
VLSR (km s-1)

Fig. 1



1981
82
83
84
85
86
87
a
G331.5-0.1
v=-95.9 km/s
100
0
b
v=-97.3 km/s
50
0
c
v=-94.6 km/s
50
0
d
v=-93.2 km/s
20
0
TEMPERATURE (K)
5000
5500
6000
6500
JULIAN DAY (244+)

Fig. 2

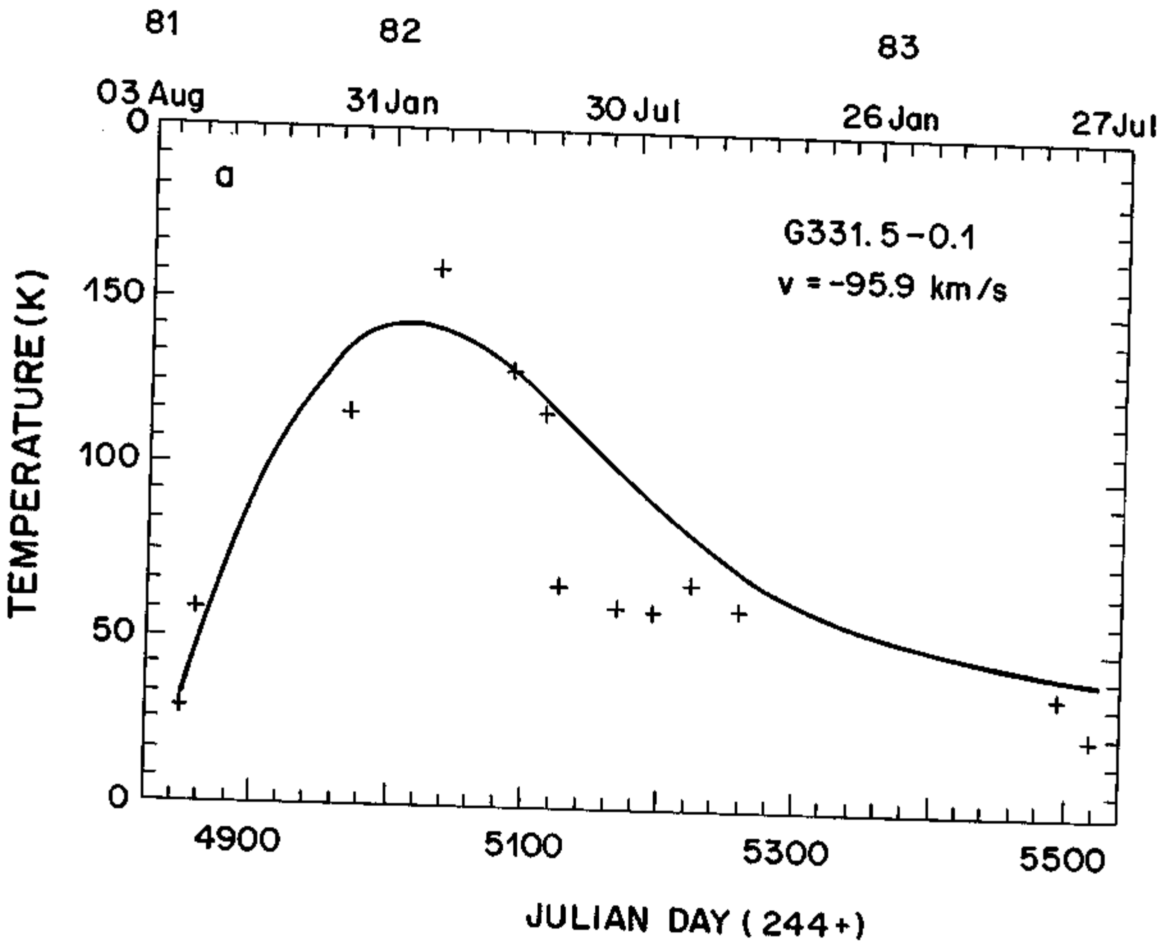

81
82
83
03 Aug
31 Jan
30 Jul
26 Jan
27 Jul
a
G331.5-0.1
v = -95.9 km/s
TEMPERATURE (K)
0
50
100
150
4900
5100
5300
5500
JULIAN DAY (244+)

Fig. 3

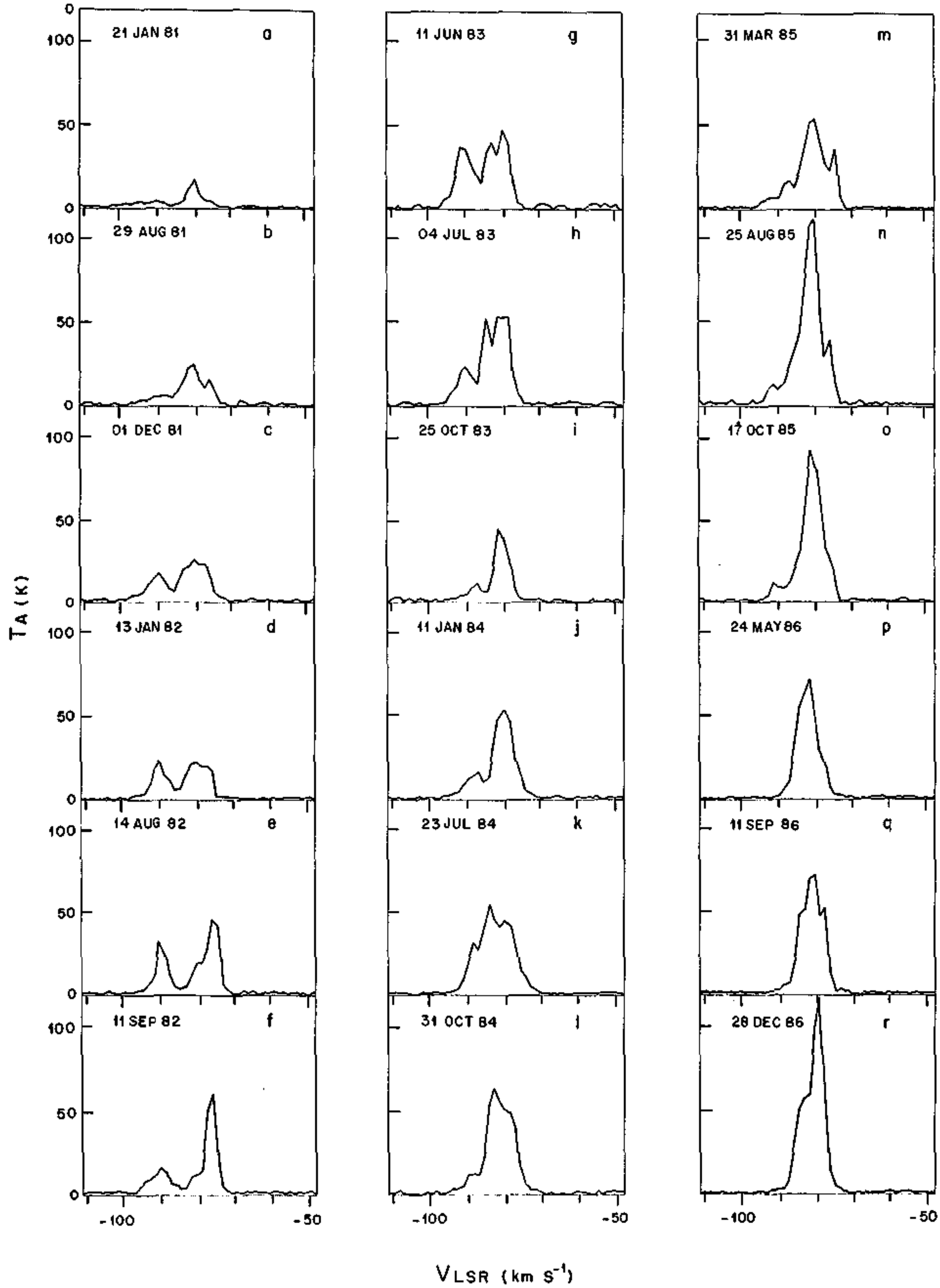
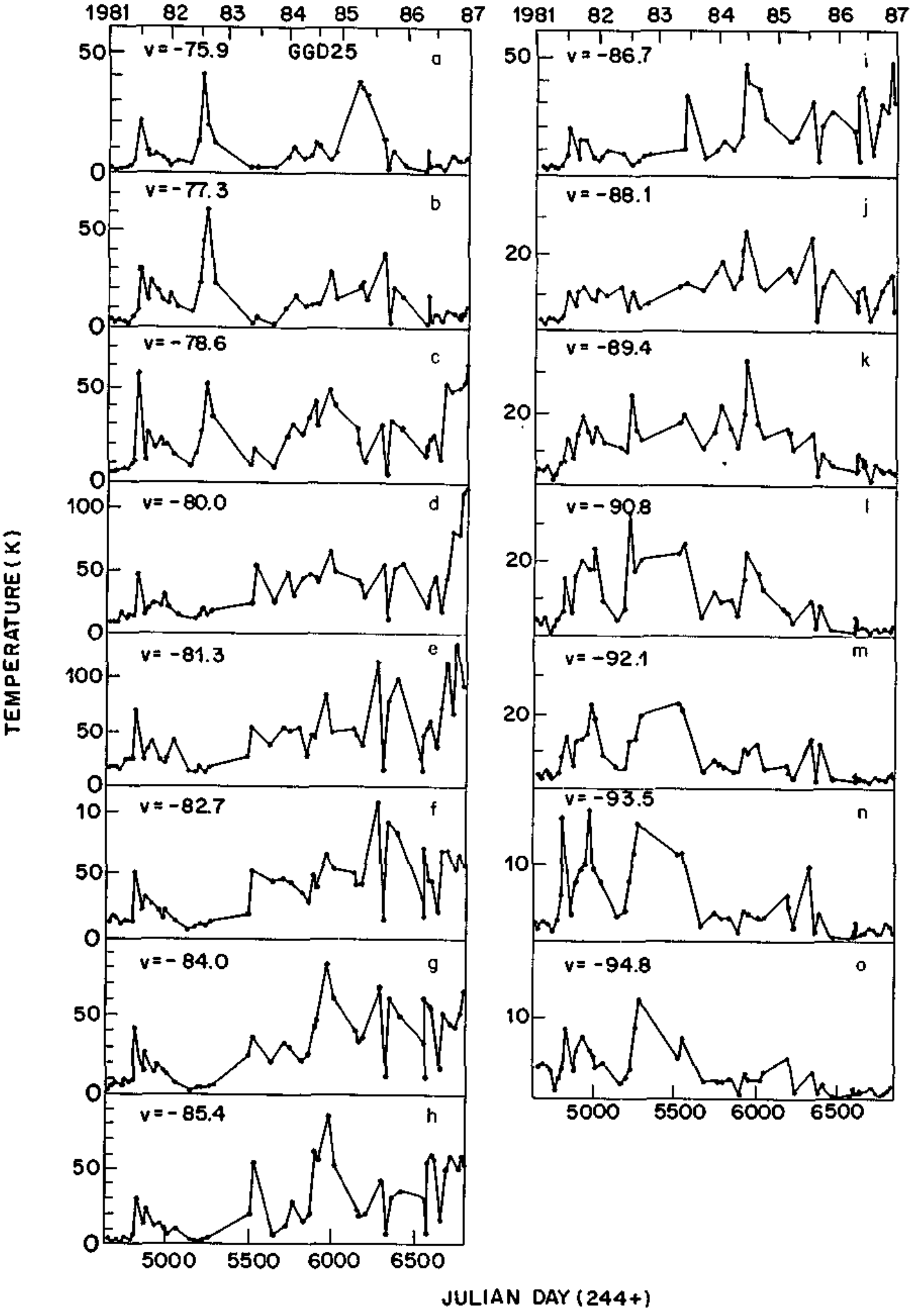

21 JAN 81
a
29 AUG 81
b
01 DEC 81
c
13 JAN 82
d
14 AUG 82
e
11 SEP 82
f
11 JUN 83
g
04 JUL 83
h
25 OCT 83
i
11 JAN 84
j
23 JUL 84
k
31 OCT 84
l
31 MAR 85
m
25 AUG 85
n
17 OCT 85
o
24 MAY 86
p
11 SEP 86
q
28 DEC 86
r
TA (K)
VLSR (km s-1)
-100
-50
0
50
100

Fig. 4



GGD25
v = -75.9
v = -77.3
v = -78.6
v = -80.0
v = -81.3
v = -82.7
v = -84.0
v = -85.4
v = -86.7
v = -88.1
v = -89.4
v = -90.8
v = -92.1
v = -93.5
v = -94.8
TEMPERATURE (K)
JULIAN DAY (244+)
1981 82 83 84 85 86 87
5000 5500 6000 6500

Fig. 5

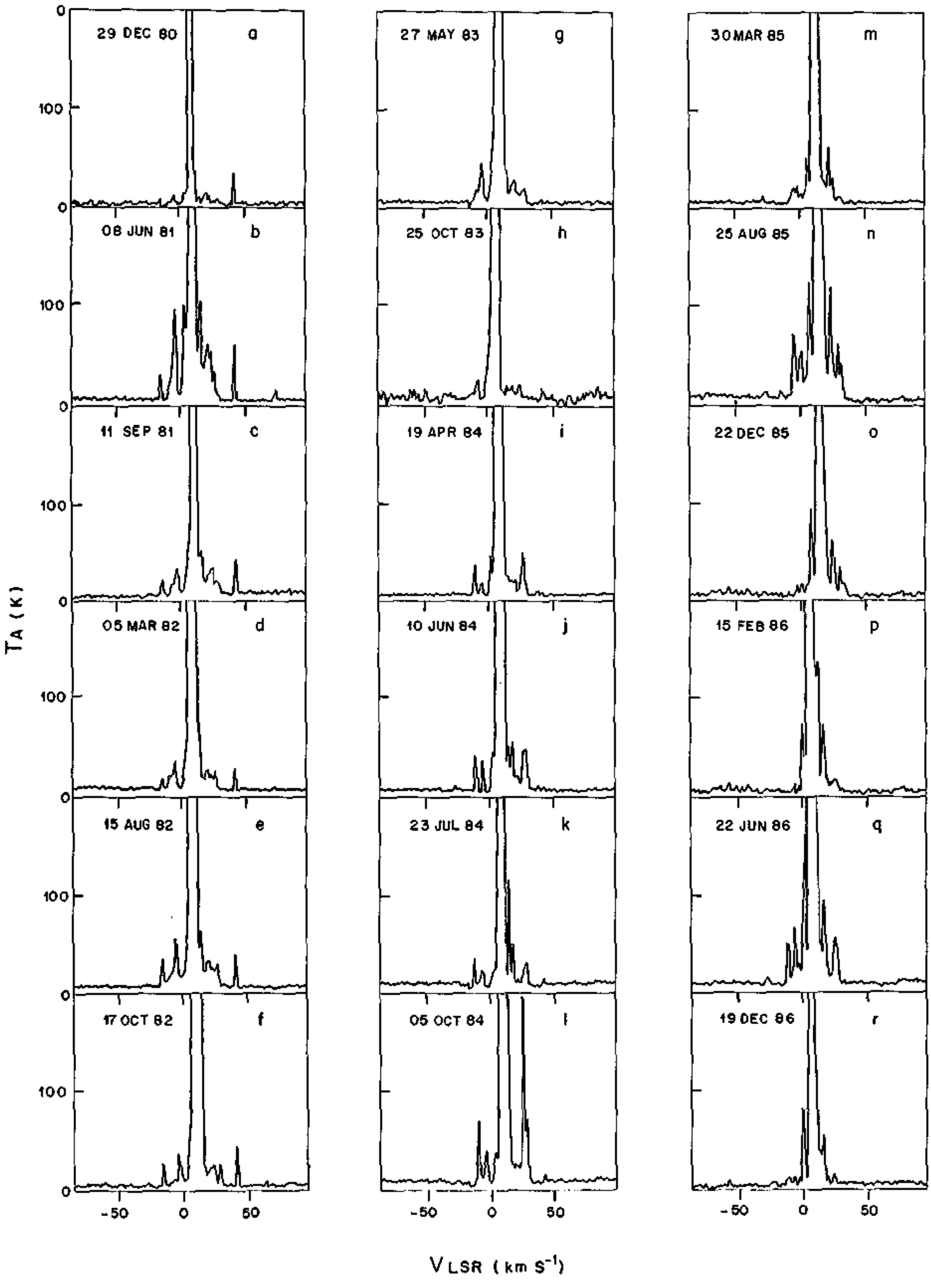
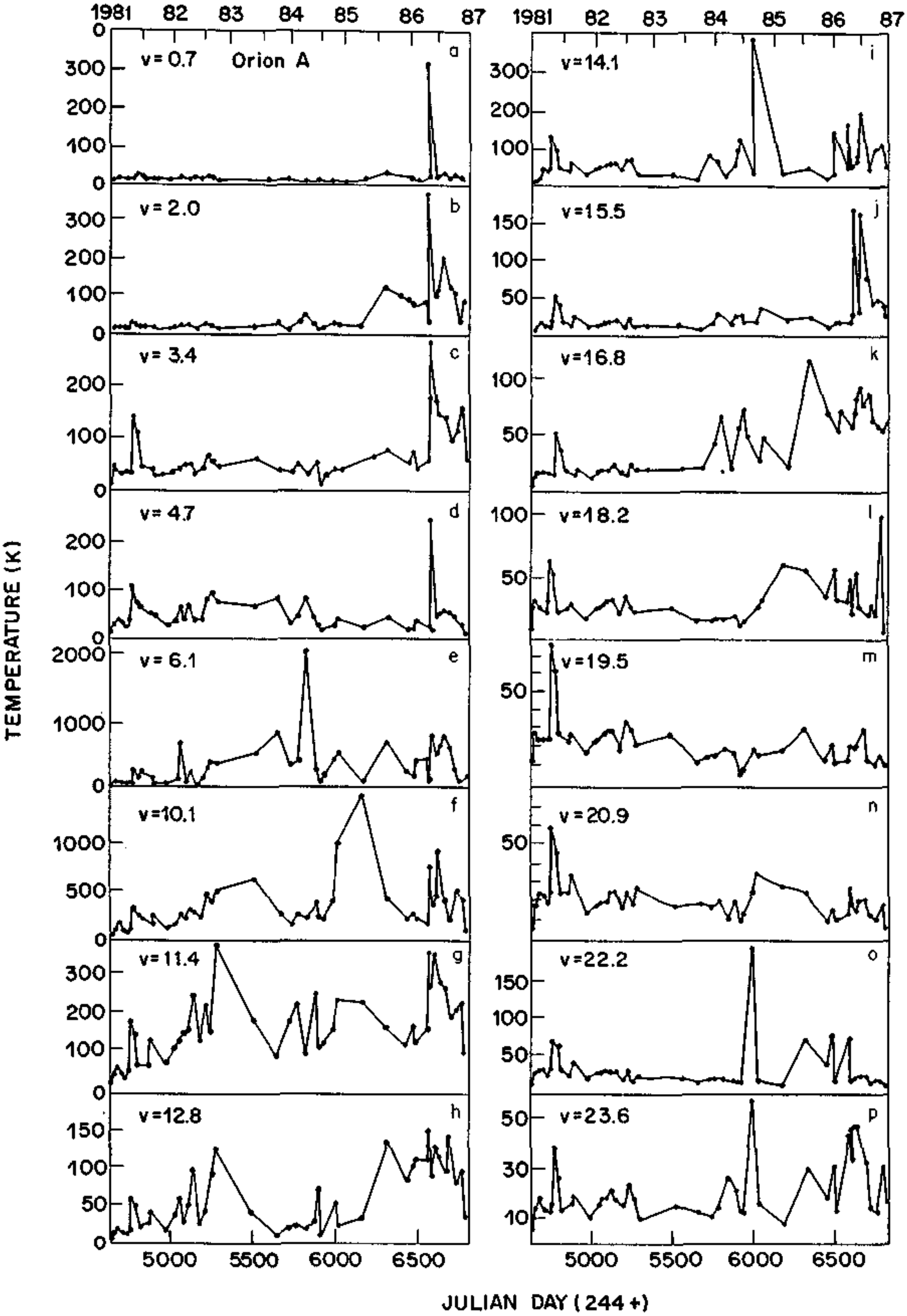

29 DEC 80
a
08 JUN 81
b
11 SEP 81
c
05 MAR 82
d
15 AUG 82
e
17 OCT 82
f
27 MAY 83
g
25 OCT 83
h
19 APR 84
i
10 JUN 84
j
23 JUL 84
k
05 OCT 84
l
30 MAR 85
m
25 AUG 85
n
22 DEC 85
o
15 FEB 86
p
22 JUN 86
q
19 DEC 86
r
0
100
-50
50
TA (K)
VLSR (km s-1)

Fig. 6



1981
82
83
84
85
86
87
v= 0.7
Orion A
v= 2.0
v= 3.4
v= 4.7
v= 6.1
v=10.1
v= 11.4
v=12.8
v=14.1
v=15.5
v=16.8
v=18.2
v=19.5
v=20.9
v=22.2
v=23.6
TEMPERATURE (K)
JULIAN DAY (244+)

Fig. 7

TABLE 1 - H_2O MASERS SOURCES MONITORED:

Source	RA (1950)	Dec (1950) (° ' ")	Maximum flux (kJy)	Velocity interval ($km\ s^{-1}$)
Orion A	05 32 47.0	-05 24 23.0	400[a)]	-77 → 87
G331.5-0.1	16 08 19.8	-51 21 02.0	7,2	-184 → -69
GGD25	17 16 56.5	-35 51 57.9	5,7	-111 → -49

a) Abraham et al. (1986)

TABLE 2 - OUTBURSTS IN THE H_2O MASERS:

Source	W3(OH)[a)]	Cep A[b)]	G305.8-0.2[c)]	G331.5-0.1
distance (kpc)	3,0	0,7	2,0	6,5
V_{LSR} (km s^{-1})	-50,4	-11,2	-26,0	-96,0
rise time (days)	8	12	8	188
flux density at the maximum (Jy)	1000	1700	1100	7200
$4\pi/\Omega$ luminosity at the maximum (erg s^{-1})	7.10^{29}	6.10^{28}	1.10^{30}	7.10^{31}
(photons s^{-1})	5.10^{45}	4.10^{44}	1.10^{46}	5.10^{47}
total energy	5.10^{35}	6.10^{34}	1.10^{36}	1.10^{39}

a) Burke et al., 1978

b) Mattila et al., 1985

c) Vilas Boas et al., 1990