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# A study of the kinematics of the $H_2O$ maser sources S269 and W75S from long-term monitoring

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**Abstract.** It is shown that basic characteristics of turbulence can be derived from temporal behaviour, shape and radial-velocity drift of a spectral line. To perform this analysis, a 20-year monitoring of the $H_2O$ maser emission sources S269 and W75S was used. It is shown that the observed sinusoidal variation of the radial velocity of the main emission feature in S269 with a period of 26 years is not caused by Keplerian motion. Most likely, it results from rotation of a non-uniform turbulent vortex with a diameter of about 1 AU. Within the framework of this model, asymmetry of the emission feature at 20.1 $\mathrm{km\,s^{-1}}$ and a jump of the linewidth, which took place after a strong flare in 1991, are explained. In W75S anticorrelation between fluxes of several emission features with close radial velocities is found. This anticorrelation is explained by competition of spatial modes of the emission for pumping in a partially saturated maser. It is shown that in the model of a maser in an expanding envelope (which is, most likely, the case in W75S) the emission features with anticorrelated fluxes form a spatially compact group.

**Key words.** masers – shock waves – turbulence – star: formation

## 1. Introduction

Observations of the $H_2O$ maser emission ($\lambda = 1.35$ cm) yield information about physical processes inside dense star-forming gas-dust clouds. In this case maser level populations are inverted at rather high densities, $n > 10^6$ cm$^{-3}$, and temperatures, $T > 400$ K (see, for example, Elitzur 1995). The observations, both single-dish and interferometric, indicate that the emission comes from multiple regions ("spots") with a characteristic size of ∼1 AU and life-time from several months to several years (see Elmegreen & Morris 1979; Genzel & Downes 1979; Plume et al. 1997; Leppänen & Liljeström 1998).

Interferometric $H_2O$ observations of the source W49N, carried out by Gwinn (1994), detected several hundred such spots, moving at various velocities, up to 200 $\mathrm{km\,s^{-1}}$ (in the frame of reference of W49N). Statistical processing of these data revealed large-scale, up to 1000 AU, supersonic turbulent motions in this source. For another source, NGC 2071, Torrelles et al. (1998) found, also in interferometric observations, a structure similar to a protoplanetary disk with a radius of only ≈20 AU. It contains 13 maser spots, probably moving in Keplerian orbits.

Observations on single-dish, even rather small, radio telescopes also yield interesting information on the dynamics of processes in the interstellar medium. In this case, time variations of maser emission spectra are analysed. For example, the three-peaked $H_2O$ spectrum in the source S255 was interpreted within the framework of three "corridors" of amplification of the maser emission in a Keplerian disk seen edge-on (Cesaroni 1990). Long-term observations of the $H_2O$ maser emission in S140 (Lekht et al. 1993) allowed us to study in more detail the motion of matter in a Keplerian disk and to isolate protoplanetary clumps in it. The presence of the clumps explains the pattern of the $H_2O$ maser emission in the star-forming region L1287 (Fiebig 1997). In this case, the fall and collision of these clumps of matter with the accretion disk results in conditions favourable for population inversion of the $H_2O$ molecules and for the maser emission.

Long-term monitoring of masers in star-forming regions traces the evolution of radial velocities of individual

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long-lived maser "spots". It is important to note that the emission intensity of a "spot" can vary depending on changing conditions of pumping and amplification of the emission. Time variability of the radial velocity, traced in sufficiently long-term observations, allows us to determine the characteristic period of motion of a spot $T_0$ and amplitude $u_0$ of the radial-velocity variations, which is, obviously, related to the basic parameters of large-scale turbulent motions in the circumstellar cloud. The scale of such a motion is estimated as $R_0 \approx u_0 T_0$.

The structure and temporal behaviour of the $H_2O$ maser emission spectrum essentially depend on the ratio of the sizes of turbulent vortices and of the masering region. If the sizes of the turbulent vortices are much smaller than those of the masering region, turbulence results in additional line broadening, $\sqrt{\Delta\nu^2_{\rm therm} + \Delta\nu^2_{\rm turb}} = \sqrt{(u^2_{\rm therm} + u^2_0)}\nu/c$. If there are several turbulent vortices inside the radiating volume, the spectrum structure strongly depends on the velocity distribution within a volume. Here, as in the case of a Keplerian disk, a characteristic three-peaked spectrum can appear, if at the vortex periphery the velocity is decreasing with the distance from the centre. Even at a solid-state rotation of a vortex, "corridors" of amplification of the emission, though less pronounced, can appear, as in the case of a Keplerian rotation.

If the turbulent vortex is larger than the masering spot (as, for example, in W49N, Gwinn 1994), the emission spectrum, probably having a complex structure, periodically varies if the vortex life-time $\tau_0 > t_0 = R_0/u_0$. For a compressible turbulence with $\tau_0 < t_0$, chaotic excursions of features' radial velocities will be observed. In both cases the presence of comparatively small-scale motions inside the "spot" results in radial-velocity fluctuations with respect to the slowly varying average value (see Lekht et al. 1999).

Thus, even kinematics alone of the motions of individual features in maser emission spectra during a sufficiently long observational interval allows us to reveal many characteristic features of the physical processes occurring in a star-forming region. The basic parameters ($u_0$, $\tau_0$ and $R_0$) thus found for turbulent motions of various scales are important for constructing more advanced models of formation of stars and planetary systems from a molecular cloud.

## 2. Data presentation

In this work we report the results of a study of the kinematics of the structures associated with groups of maser spots. For this purpose we have analysed the spectra of a number of water-vapour maser emission sources in active star-forming regions. The first condition of the existence of such groups of spots was that during several years these groups were more or less isolated in the $H_2O$ spectra with respect to other spectral components. The second condition was mutual spectral drift of at least two features within a group. Finally, the third condition was defined by the timescale of these features' relative motion. As a rule, it was not shorter than one year. As a database we have used the $H_2O$ spectra obtained on the RT-22 radio telescope of the Pushchino Radio Astronomy Observatory.

The antenna beamwidth at 22 GHz is 2$'$.6. The observations were made using the "ON–ON" method together with a symmetrical beam switching. In addition, the antenna was directed to the source by one feed horn and then by the other one. During the former stage, a calibration signal from a noise gas–discharge tube was injected for some time. A noise tube in its turn was calibrated against noise signals of heated and cooled loads and by observations of Jupiter.

We used a 22–GHz maser amplifier, cooled by liquid helium, and in 1997–2000 a cooled transistor amplifier. The noise temperature of the receiving system was about 200–300 K. In 2000 the modernization of the radiometer was carried out, which allowed us to reduce the temperature of the system up to 100–130 K.

The receiver backend was a 128-channel filter-bank spectrometer with a frequency resolution of 7.5 kHz (0.101 km s$^{-1}$ at the $H_2O$ frequency). The necessary frequency band was covered by returning the frequency of the local oscillator. A quartz oscillator was the frequency standard, which was used to phase lock the clistron local oscillator. An antenna temperature of 1 K for an unpolarized source corresponds to a flux density of 25 Jy. The equipment and observational procedure were described detail by Sorochenko et al. (1995).

After a preliminary analysis we chose two sources, S269 and W75S. Results of monitoring of the $H_2O$ maser S269 in 1980–2001 were published by Lekht et al. (2001). From this work we have used the line profiles of the emission feature at 20.1 km s$^{-1}$.

Figure 1 presents selected $H_2O$ spectra (fragments) of S269 to show the existence of the drift. The horizontal axis is the radial velocity in km s$^{-1}$, referred to the Local Standard of Rest (LSR), and the vertical axis is the flux density in Janskys. The main emission feature at $V_{\rm LSR} \approx 20.1$ km s$^{-1}$ was observed throughout our monitoring of S269 from 1981 to 2001. The other feature had an average radial velocity of about 17 km s$^{-1}$. We observed it from 1981 to 1994, and then this emission appeared only episodically (Lekht et al. 2001). We observed the radial-velocity drift of both features; a relative change of the features' radial velocities also took place (Fig. 2). Figure 2a is taken from Lekht et al.(2001); in that work we reported only the detection of a sinusoidal variability of the radial velocity for the emission feature at 20.1 km s$^{-1}$.

To understand the observed drift of the features, we have traced the linewidth variations. The point is that in the case of several overlapping features (close in velocity) with changing ratio of the features' amplitudes the total spectrum can drift in radial velocity. Furthermore, the width and shape of the line will vary. The observed variability of the flux and linewidth of the 20.1-km s$^{-1}$ feature is shown in Fig. 3.

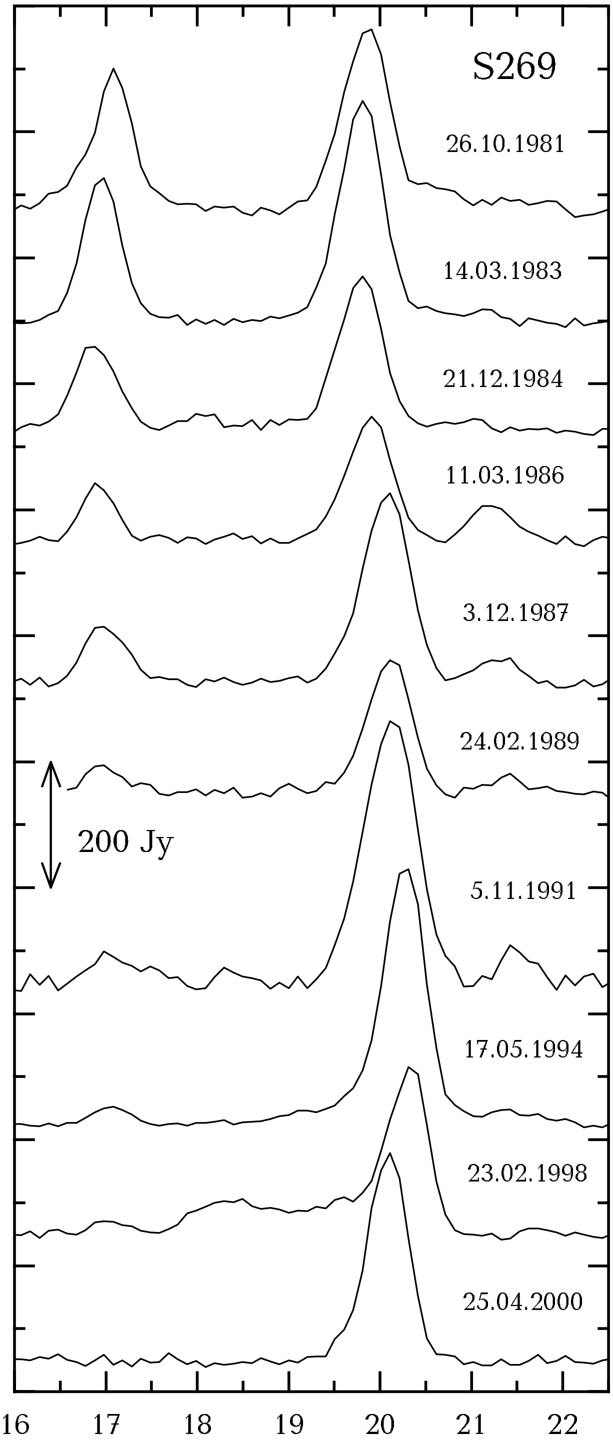


**Fig. 1.** Fragments of some spectra of the $H_2O$ maser S269 for 1980–2001.

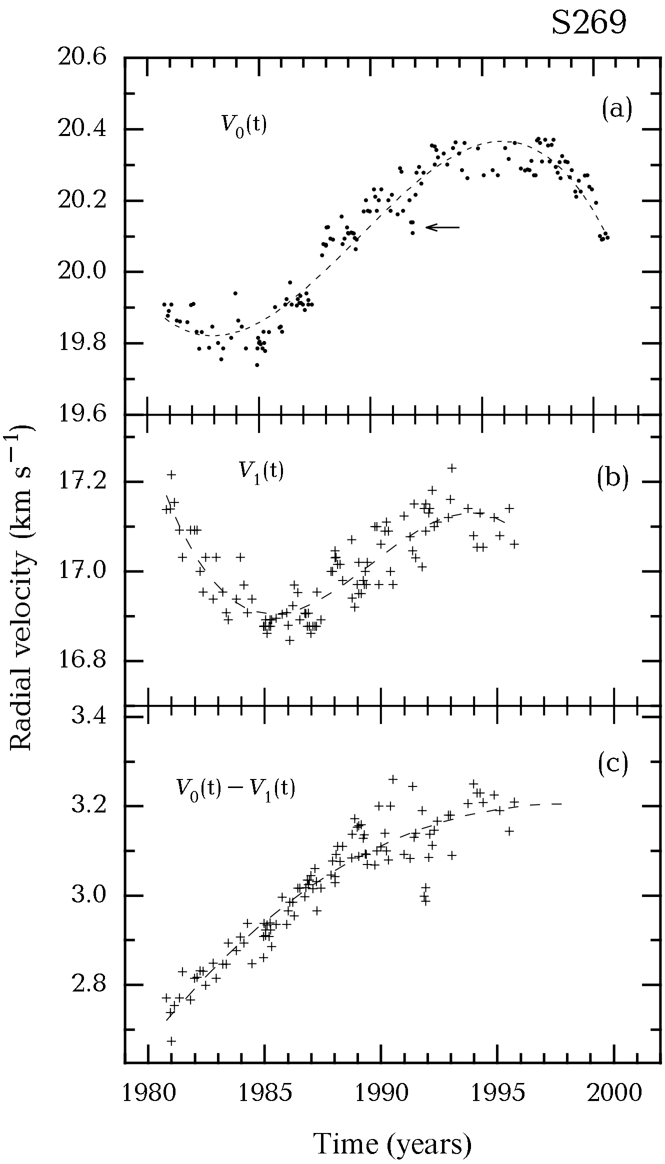


**Fig. 2.** Variability of radial velocity and velocity differences of the two main emission features in the $H_2O$ maser S269. The arrow indicates the points corresponding to the maximum of the flare of 1991.

For this emission feature we have searched a correlation between flares of the flux and the linewidth variations. For single features of other sources in the case of an unsaturated or partially saturated maser, we observed line narrowing as the flux was growing and vice versa. For our analysis we have divided the 1981–2000 interval into 15 sections with different durations. Each section was selected according to one of the two criteria. The first criterion was that within each section the flux and linewidth were varying more or less monotonically. According to the second criterion, on the contrary, in the limits of the subinterval there were significant and fast changes of the flux, as, for example, during the flares at the end of 1986 and at the end of 1991. Within each time interval all the spectra (of the main emission feature) were normalised in amplitude and superposed in radial velocity. Then we calculated the average spectra (this allowed us to eliminate random errors in individual spectra) and average radial velocities.

The observed lines were rather narrow, i.e., the resolution bandwidth of our filter-bank spectrum analyzer ($\Delta f = 7.5$ kHz) was not much narrower than the linewidth. As a result, the line shapes observed were somewhat distorted. For this reason the average spectra were

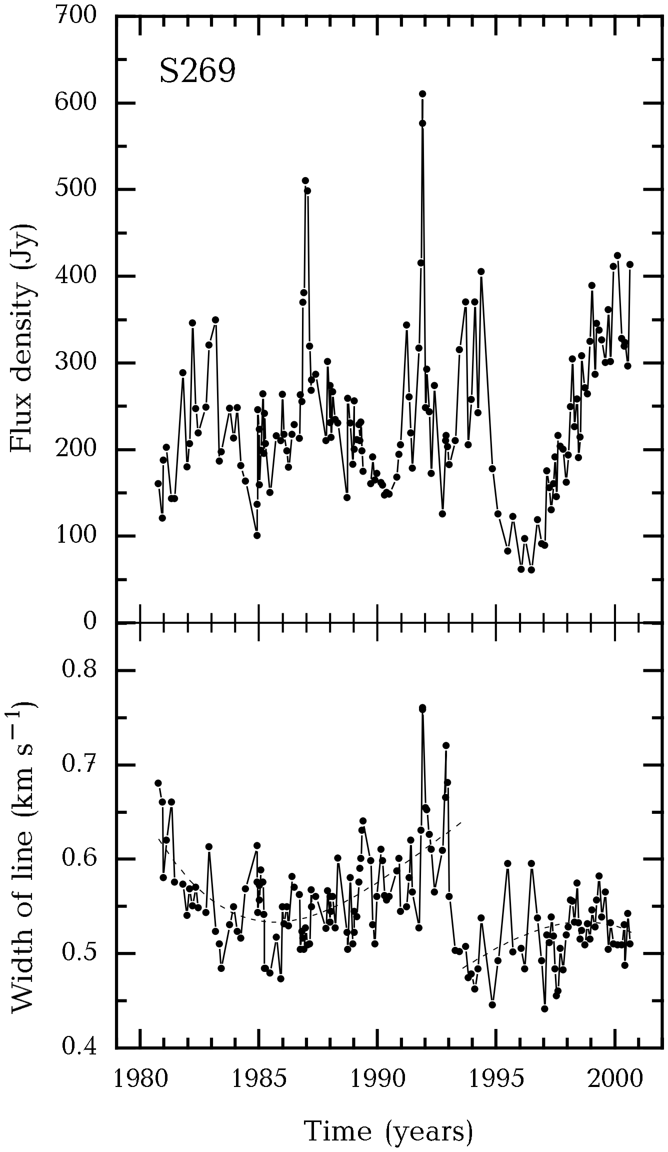


**Fig. 3.** Variability of the flux and linewidth of the emission feature at $V_{LSR} = 20$ km s$^{-1}$ of the $H_2O$ maser S269.

corrected. Then to each average spectrum a Gaussian was fitted. The results of this procedure are presented in Fig. 4. A comparison of the average spectra with the corresponding Gaussians has shown that there is a small asymmetry of lines, which is always maintained, irrespective of the linewidth variations. The left-side (low-velocity) wing of a line is flatter than the right-side (high-velocity) one. Therefore, the line peak is slightly displaced with respect to the Gaussian fitted for each time interval.

Figure 5 presents for W75S the spectra with similar structures, obtained at different epochs. The graph axes are the same as in Fig. 1. In addition to this, for the period from the end of 1987 to the middle of 1991, individual spectral components were revealed. They had close radial velocities and fast flux variations. Two components with radial velocities of $-5.9$ and $-5.4$ km s$^{-1}$ from time to time appeared in the spectra, alternatively replacing each other (Fig. 6). These components were absent in the spectra between the end of 1989 and the beginning of 1999, when there was a strong emission on $-4.5$ km s$^{-1}$ with a peak flux of 1170 Jy and weaker emission at $-6.9$ km s$^{-1}$ with $F_{\max} = 390$ Jy. In Fig. 6 the positions of the strongest maxima are shown with circles, and figures above them designate their flux densities in Janskys.

## 3. Discussion

### *3.1. Variations of the radial velocity and line shape of the 20.1-km s$^{-1}$ emission feature in S269*

In the $H_2O$ spectra of the source S269 during 1980–2001, we observed four most intense and long-lived emission features. According to Lekht et al. (2001), two of them were most intense and, of special importance for us, they are in one of the two groups of maser spots (Migenes et al. 1999). Both features drifted in radial velocity (Fig. 2). The drift reality was confirmed by their relative motion (bottom graph of Fig. 2).

The variability curve of the main-component radial velocity (20.1 km s$^{-1}$) $V_0(t)$ corresponds to a sinusoidal time variation (Fig. 2). Such character of the variability can be a consequence of periodic motion of a clump of matter in a circular or elliptical trajectory at a velocity of 0.27 km s$^{-1}$ and period of 26 years. If the plane of motion of the clump is observed edge-on, the trajectory radius is about $0.4 \times 10^{13}$ cm, and diameter, i.e., total size, is $0.8 \times 10^{13}$ cm. Assuming the most probable inclination angle of the orbit of about 45° yields a diameter of $1.1 \times 10^{13}$ cm.

Of course, the curve of the radial-velocity variability, $V_0(t)$, could be obtained by superposition of several features whose flux was changing with time in such a manner that the position of the total-emission peak would be described by the observed $V_0(t)$ curve. However, the analysis of the line shape shows that the displacement of the line in the spectrum is real. A superposition of several components, to get line peak excursions within 0.6 km s$^{-1}$, would result (at least, in some periods of time) in a strong line broadening and, in particular, in its plateau-like shape. Throughout our monitoring of S269 we never observed such broadening or line shape (see Fig. 4). Thus, the $V_0(t)$ curve may correspond to actual rotation of the masering region with a radius of not less than $(0.5\text{–}0.6) \times 10^{13}$ cm.

This motion cannot be Keplerian for two reasons. First, at $V = 0.27$ km s$^{-1}$ and $R = 0.55 \times 10^{13}$ cm from the known formula of circular motion in a Keplerian orbit

$$V = \sqrt{\gamma M/R} \quad (1)$$

we obtain that the mass of the central body $M \approx 6 \times 10^{28}$ g. It most likely corresponds to a mass of a small planet (the mass of the Earth is $6 \times 10^{27}$ g), instead of the mass of a protostar. Second, in the case of a Keplerian disk there is a triplet structure of the $H_2O$ spectrum, which suggests the existence of three corridors of amplification of

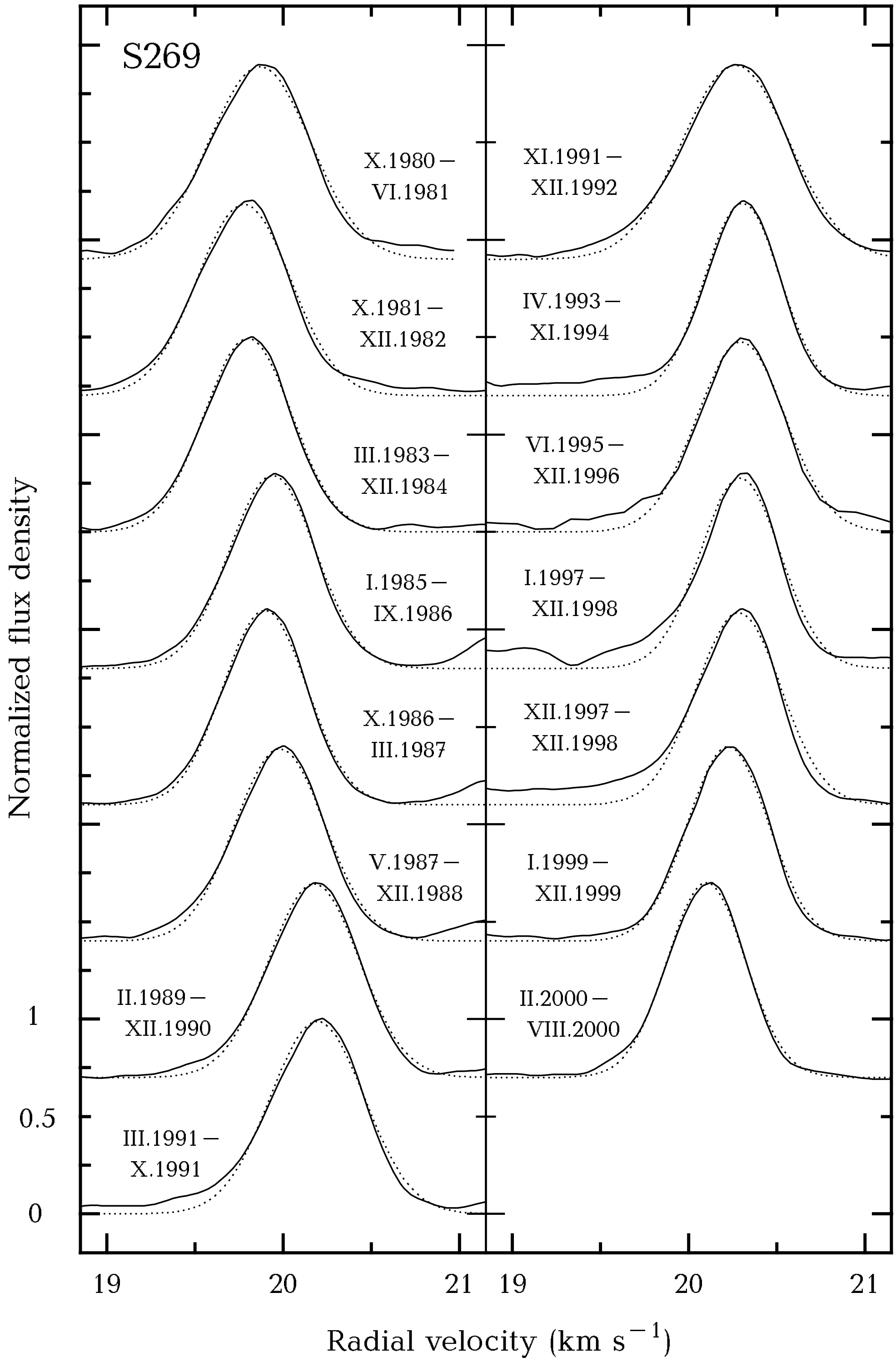


**Fig. 4.** Average normalised spectra for the emission feature at 20 km s$^{-1}$ of the $H_2O$ maser S269 for various time intervals.

the maser emission: one central and two lateral (Cesaroni 1990; Lekht et al. 1993). If the clump of matter makes a complete revolution in an orbit, its radial velocity should vary within the limits of the velocities of lateral corridors of amplification. For S269 it is about $\pm 8$ km s$^{-1}$ relative to the velocity of the central component (Lekht et al. 2001); this by more than an order of magnitude exceeds the observed radial-velocity variations of the component at 20.1 km s$^{-1}$.

Thus, the drift of the feature with the average radial velocity of 20.1 km s$^{-1}$ of the source S269 most likely corresponds to turbulent rotation of the active masering region in the presence of an inhomogeneity in it. The existence of large-scale turbulent motions in the interstellar

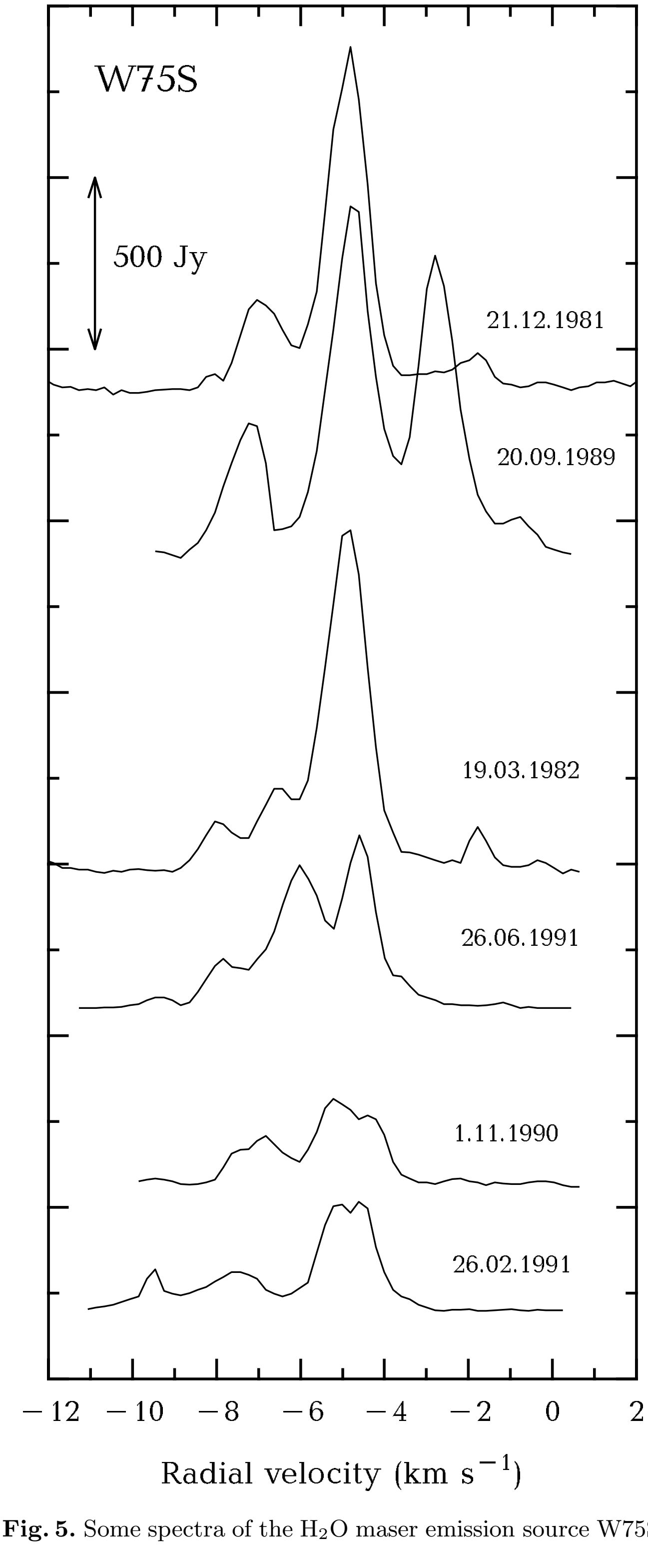


**Fig. 5.** Some spectra of the $H_2O$ maser emission source W75S, obtained on the RT-22 radio telescope of the Pushchino Radio Astronomy Observatory.

medium has been shown in many works (see, for example, Scalo 1990; Gwinn 1994).

During all the 20 years of its observations, the profile of this spectral component had a significant asymmetry (Fig. 4). What is the cause of this asymmetry? Within the framework of the Keplerian-disk model, the corridor

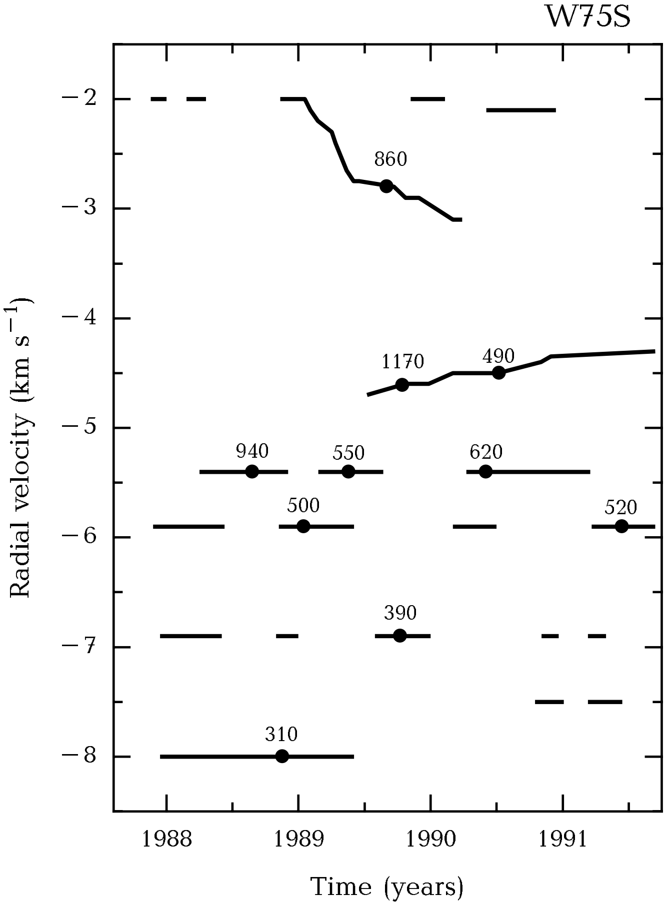


**Fig. 6.** Schematic evolution of the main emission features of W75S at radial velocities from −8 to −2 km s$^{-1}$ in 1987.8–1991.4. Circles denote the positions of the strongest maxima, and numbers above them give flux densities in Janskys.

of amplification is limited by the Doppler velocities; this is necessary to satisfy the condition of coherence of the molecules in radial velocity.

First we consider the case of amplification of the emission in a homogeneous amplifying corridor (see Fig. 7). For convenience we rewrite formula (1) as

$$V_{\mathrm{k}} = V_0\sqrt{R_0/R}, \qquad (2)$$

where $R$ is the distance from the star, and $V_0$ is the velocity at distance $R_0$. Within the corridor of amplification $R$ and $R_0$ are connected by relationship $R = R_0 \cos\varphi$, and formula (2) can be written as $V_{\mathrm{k}} = V_0\sqrt{\cos\varphi}$. The line-of-sight component of this velocity is $V = V_0(\cos\varphi)^{3/2}$. This formula displays a nonlinear variation of the radial velocity along the corridor of amplification. In S269 the corridor of amplification will be limited to the opening angle $\varphi \approx \pm 10°$. With this restriction, calculations for a homogeneous corridor of amplification at $\tau \approx 20-30$ give the required linewidth with an asymmetry of 1.5−2% (the left-side wing is higher than the right-side one).

The effect of asymmetry can be enhanced if the medium within the corridor of amplification is non-uniform. For example, we can place the "vortex" at the

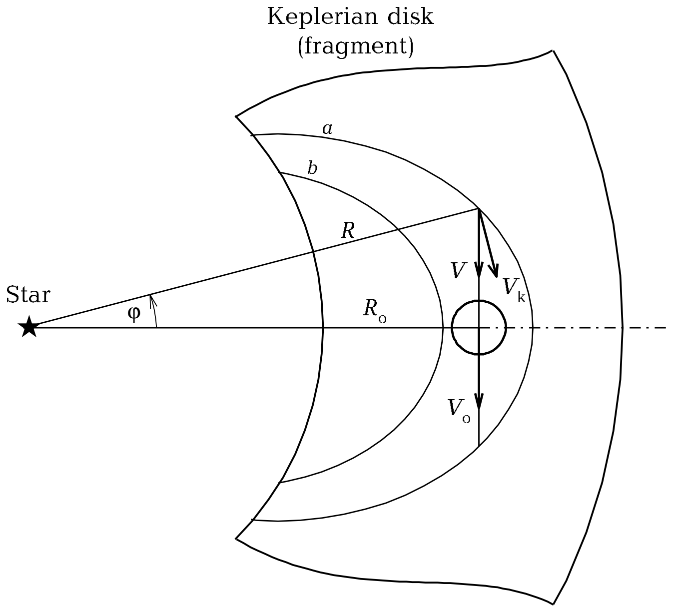


**Fig. 7.** Model of the $H_2O$ maser for the emission feature at 20.1 $km\,s^{-1}$ in S269. Two curves (a and b) of the constant radial velocity restrict the volume where the $H_2O$ molecules have the velocity difference within the Doppler line width. The circle denotes the position of a vortex.

centre of the corridor. The basis for this is the fact that during the 20-year period of the observations we found no regular drift of the emission feature at 20.1 $km\,s^{-1}$. The minimum rate of the radial-velocity variation will be precisely at the corridor centre. In this model the line asymmetry equal to the observed one is achieved.

### 3.2. Correlation of variability of the flux and linewidth of the emission feature at 20.1 $km\,s^{-1}$

Before 1991 we observed no correlation between the flux and linewidth variations. In 1991 the strongest $H_2O$ flare happened in S269. As a rule, in an unsaturated or partially saturated maser, as the flux grows, the line narrows. We did not observe this in S269. On the contrary, we observed considerable line broadening (Fig. 3). In addition to this, there was a small displacement of the line peak in the radial velocity (see Fig. 2). Later on (see Fig. 3), at the descending branch of the flare, the line was at first narrowing and then again broadening. The widest line was observed at the minimum flux (October 1992). After that the flux began to increase, but not so rapidly as in the flare of 1991. However, at the beginning of 1993 a sharp and significant decrease of the linewidth to 0.5 $km\,s^{-1}$ occurred. In all what followed, the linewidth varied with respect to this value. The smoothed variations of the linewidth are shown with dashed lines. The linewidth jump is readily visible.

We can assert that the linewidth jump is directly connected to the flare of 1991. This short-lived flare could be a consequence of passage of a shock wave through the maser condensation at 20.1 $km\,s^{-1}$. The time of the flux growth to the maximum value was 5 months. Let us accept this value as the time during which the shock passed through the maser condensation. With a shock velocity typical for circumstellar envelopes, 10–15 km $s^{-1}$ (Cochran & Ostriker 1977), we obtain a size of the masering region of $\sim 2 \times 10^{13}$ cm, which is in a good agreement with the value of $1.1 \times 10^{13}$ cm found in Sect. 3.1.

Thus, we deal with a structure of about 1 AU in size. Precisely such sizes for individual maser "spots" are obtained from VLBI observations. The linewidth jump, which occurred one year after the strong flare of 1991, could be a consequence of change in the geometry of a rather stable maser "spot". This stable, long-lived structure is not simply a condensation of matter and not simply the necessary column density of coherent molecules on the line of sight (cylindrical maser). To explain all the observed phenomena, the most suitable is the model of a clump of matter in the form of a rotating turbulent vortex. This assumption is also consistent with the work of Fiebig (1997), who developed a model of the $H_2O$ maser arising in the collision of a rotating clump with the accretion disk around a protostar. As we have shown above, the observed minor asymmetry of the line can arise if the water-vapour molecules in the corridor of amplification participate in the Keplerian motion.

### 3.3. Structure of the $H_2O$ spectra of the source W75S

A comparison of the $H_2O$ spectra of W75S, obtained in our long-term monitoring on RT-22 in Pushchino, has shown similarity in the spectrum structure at different epochs. This means that in W75S we observe emission features at sufficiently close radial velocities, but separated in time by 5–10 years (Fig. 5). The recurrence of similar spectra is an argument that in W75S there exist stable structures, whose radial velocities virtually have not changed during many years.

We have analysed the evolution of the $H_2O$ spectra of W75S for one of the maser activity cycles of this source, from the end of 1987 to the beginning of 1991 (Lekht et al. 1995). In spite of a strong variability of the spectra in this period and the presence of a large number of emission features with close radial velocities, we could isolate individual components (Fig. 6). We should especially mention two features at $V_{LSR} = -5.9$ and $-5.4$ $km\,s^{-1}$, which in turns appeared in the spectra, sometimes replacing one another, i.e., the fluxes of these two features were anticorrelated. From September 1989 to February 1990 the emission of these features was absent at all. However, there was a strong emission at a radial velocity of $-4.6$ $km\,s^{-1}$ with a flux of 1170 Jy and a weaker one at $-6.9$ $km\,s^{-1}$.

The observed anticorrelation of fluxes, which took place for several emission features, could be caused by a series of shock waves, which consecutively passed through the clumps of matter and excited maser emission in them. However, in our view, a different reason is more preferable.

We should note that the flux anticorrelation took place for features with close radial velocities; this essentially distinguishes W75S from S140 and S255, which are identified with Keplerian disks. In S140 and S255 the flux anticorrelation was observed for components widely separated in velocity, which were localised in different corridors of amplification. The flux anticorrelation occurs because of competition of spatial modes of emission for pumping in a partially saturated maser. For the masering molecules to be coherent, they should not move relative to each other. In an expanding envelope this condition is satisfied for clumps of matter located compactly.

According to Genzel & Downes (1979), there are several maser sources in the W75S region. Within the RT-22 telescope beam there are the main source, W75S(2), and the weaker one, W75S(1). The signal of the latter source is attenuated by the antenna beam by a factor of 3 relative to W75S(2). Within the limits of the measurement errors, the main source W75S(2) forms two groups of maser spots (2a and 2b). These two groups probably have a common envelope and common activity centre. From VLBI observations (Johnston et al. 1977) it can be accepted that the diameter of this system is $1.8 \times 10^{17}$ cm. The existence of a shell structure in W75S(2) and the observed flux anticorrelation results in the conclusion that at least four components with anticorrelated fluxes form a spatially compact group.

## 4. Conclusion

Long-term, more than 20-year monitoring of the $H_2O$ maser emission sources S269 and W75S has allowed us to study the kinematics of some selected emission features in these sources. Below we summarise the main results of our study.

1. We have shown that a sufficiently long-term monitoring of maser sources basically allows us to get characteristic parameters of turbulence in the interstellar medium, $u_0$, $R_0$ and $\tau_0$, or some relationships between them ($u_0$ is the amplitude of turbulent pulsations, $R_0$ is the characteristic scale of turbulence, and $\tau_0$ is the lifetime of the turbulent structure).

2. We have found that the radial velocity of the main emission feature in the water-vapour maser source S269 in 1980–2001 was varying in a sine wave with an amplitude of 0.27 $\mathrm{km\,s^{-1}}$ and period of 26 years. It is shown that these velocity variations do not correspond to any Keplerian motion of a clump of matter in an accretion disk. Most probable is the model of a maser spot as a nonuniform rotating turbulent vortex with a diameter of about 1 AU. This may be an evidence for "intermediate-scale" turbulence in the star-forming region.

3. We observed a jumplike narrowing of the emission feature at 20 $\mathrm{km\,s^{-1}}$ in the source S269. This line narrowed from 0.65 to 0.5 $\mathrm{km\,s^{-1}}$ after the strong flare in 1991. The cause may be a change of the maser structure after the strong flare, induced by passage of a shock wave.

4. During all our monitoring we observed the line asymmetry in the emission feature at 20.1 $\mathrm{km\,s^{-1}}$ in the source S269. This asymmetry can be caused by of the clump of matter (turbulent vortex) is in a corridor of amplification in which the $H_2O$ molecules have a Keplerian motion. In this case, the low-velocity line wing will be flatter than the high-velocity one, which is what we observed.

5. In the source W75S we have found anticorrelation of fluxes of four emission features with closeby radial velocities. These features may form a compact spatial system in an expanding envelope. Competition of spatial modes of emission for pumping (in the case of a partially saturated maser) results in anticorrelation of fluxes of these emission features.

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