Star-Disk Interaction in Young Stars
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The structure accompanying young star formation

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Abstract. We studied the structure of the H_2O super maser region in Orion with VLBI angular resolution of 0.1 mas or 0.05 AU. The maser emission (F $\sim$ 8 MJy) was determined by highly organized structure: accretion disk, bipolar outflow, torus and surrounding shell. The accretion disk, divided into protoplanetary rings, is viewed edge-on. The disk rotates as a rigid body with velocities $V \sim \Omega R$ and the rotation period is $\sim$ 170 yrs. The highly collimated bipolar outflow has a size of 9×0.7 AU, a velocity of $\sim$ 10 km/s. In the center a bright compact ($\leqslant$0.05 AU) source ejector is located, surrounded by a torus 0.6 AU in diameter. The outflow has a helix structure, which is determined by precession with a period of T $\sim$ 10 yrs. Comet-like bullets were observed on distances up to 80 AU.

Keywords. Jets, bipolar outflows, accretion disk, maser.

1. Introduction

Gravitational instability in gas-dust complexes gives rise to active regions of protostar formation. The formation of protostars is accompanied by strong maser emission in water-vapor lines, its flux density reaches several tens of kJy. In extremely rare cases, intense H_2O maser flares are observed; their nature and triggering mechanism are not yet completely clear (Burke, Johnston & Efanov 1970; Matveyenko, Kogan & Kostenko 1980). In the Orion Nebula, compact maser sources are concentrated in eight zones whose sizes reach $\sim$ 2000 AU (Genzel *et al.* 1978). The velocities of the maser sources are within several tens of km/s. There was two high activity periods in one of the zones in Orion KL – 1979-1987 and 1998-1999. The radio flux densities of H_2O maser flares reached 8 MJy, and the linewidth of the profile was $\sim$ 0.5 km/s. The velocity of outbursts changed only slightly relative to V = 8 km/s. The coordinates of the active region are $RA = 5^h 35^m 14^s.121$ and $DEC = -05^0 22^{'} 36^{''}.27$ (2000.0). Below, we analyze in detail the structure of the active supermaser emission region over the period under consideration(Matveyenko, Graham & Diamond 1988; Matveyenko, Diamond & Graham 1998).

2. High activity – epoch 1979-1987

The period of high activity 1979-1987 was accompanied by intense H_2O maser outbursts. The flux densities of the maser outbursts reached F = 1 − 8 MJy, and some of them had a duration of a few days; on average, the enhanced activity lasted for several months (Abraham, Vilas Boas & del Ciampo 1981; Matveyenko 1981; Garay, Moran & Hashick 1989). The supermaser had Gaussian profile with a high-velocity or low-velocity tail.

The profile consists of several features, which are indicative of a complex spatial structure. The observed change of profile velocity V $\simeq$ 8 km/s is determined by the relative

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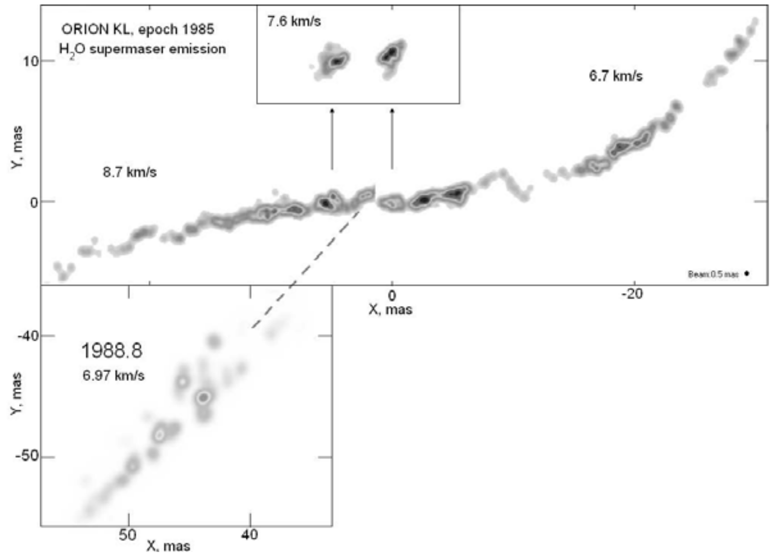

Figure 1. An accretion disk, divided into protoplanetary rings, seen edge-on.

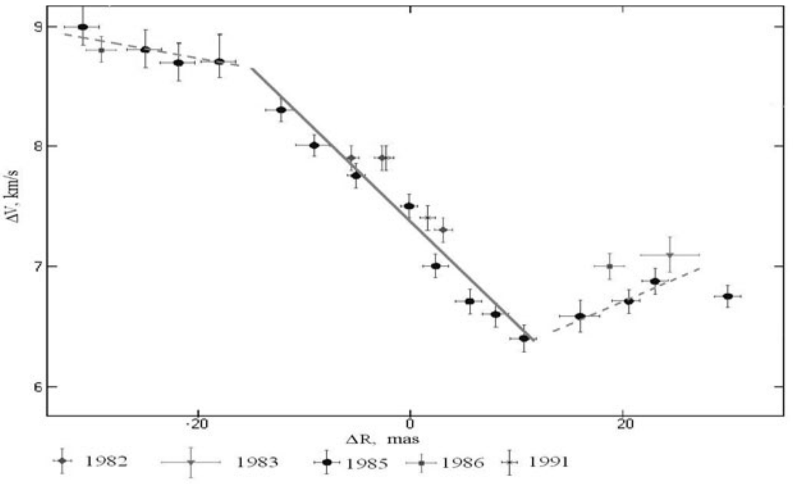

Figure 2. Velocities of the compact components in the disk, $V_{LSR} = 7.6 km/s$.

contribution of the features. The linewidth at half maximum (FWHM) of the line profile is $\Delta V \simeq 0.5$ km/s. VLBI measurements of the active region in Orion KL showed that the maser emission in the period under consideration is determined by a highly organized structure, a chain of compact components (Matveyenko 1981). The most complete VLBI measurements were performed in October 1985. A detailed analysis revealed both an extended structure of low brightness, $T_b \sim 10^{11}$K, and a superfine component of high brightness, $T_b \sim 10^{16}$K. The structure consists of a chain of bright compact components distributed along a thin, $\sim$ 0.3 AU, extended S-shaped structure $\simeq$ 27 AU in length (Fig. 1). The velocity of the active region is $V_{LSR} = 7.6$ km/s (Matveyenko, Diamond & Graham 1998). The velocities of the individual components of the structure are also indicated here (Demichev & Matveyenko 2004). The two components located in the central part of the chain have the highest brightness temperatures, reaching $T_b \sim 10^{16}$ K. The radial velocities and brightness temperatures of these components are V$_E$ =

7.50 km/s, $T_b \sim 10^{16}$ K and V_W = 7.75 km/s, $T_b \sim 0.6 \times 10^{16}$ K. They contain compact cores ~0.05 AU in size, with brightness temperatures reaching $T_b \sim 4 \times 10^{16}$ K.

The velocity distribution of the components is shown in Fig.2. In the central part of the structure within $\simeq$ 15 AU we have linear velocity change dV/dR = 0.17 km/s/AU. The components correspond to the tangential directions of the concentric rings seen edge-on. Their velocities are equal to the rotation velocity. In this case, the central part of the structure is rotating as a rigid body $V_{rot} = \Omega R$ with period of T $\simeq$ 170 yr.

The brightness of the features in the chain declines with increasing distance from the center to $T_b \sim 10^{12}$ K at its edges. The outer shape of the disk is deformed, probably by interaction with accreting matter. The velocities of the outer parts of the chain deviate from the linear dependence in its central part (Fig. 2). The outer part of the disk is outside the region of rigid body rotation and has a mean rotation velocity of $V_{rot} \simeq 1.1$ km/s, and a radius of R $\simeq$ 14 AU. Its rotation velocity may be determined by Keplerian motion, $V^2 R = MG$. In this case, the total mass of the inner part of the structure is $\leqslant 0.02 M_\odot$ (Matveyenko, Demichev & Sivakon 2005). The ambient medium/envelope amplifies maser emission on velocity V $\simeq$ 7.65 km/s in a 0.5 km/s band (Matveyenko, Graham & Diamond 1988).

A fine elongated structure consisting of bullets was detected at a distance of 30 AU from the center of the chain in the direction PA = 135^o at the end of the period of high activity 1988-1989.

3. Quescent period – epoch 1995

Observations of the active region in the period of low activity (the epoch 1995.6) showed that the H_2O maser emission at a velocity of 8 km/s does not exceed 1 kJy. VLBI studies with an ultrahigh angular resolution 0.1 mas (0.045 AU) revealed a highly collimated bipolar outflow with a bright compact central source, but the chain of components was absent or its emission was below the detection limit (Fig. 3; Matveyenko, Diamond & Graham 1998). The bipolar outflow 4.5 x 0.5 AU is oriented at PA = -33^o, and its brightness temperature is $T_b \sim 10^{12}$ K.

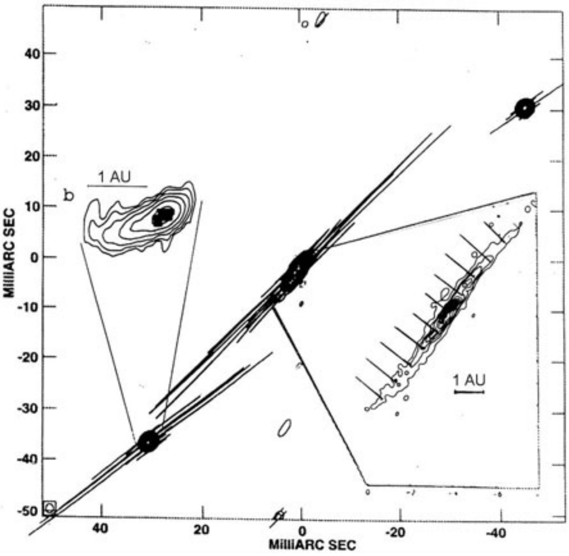

Figure 3. Bipolar outflow and bullets in quescent epoch 1995.6.

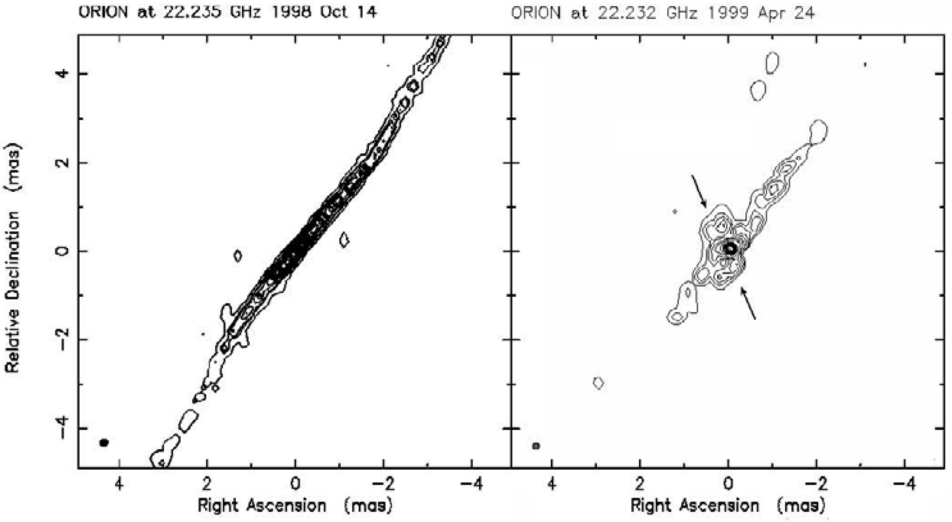

Figure 4. Bipolar outflow on 14 oct 1998 (left) and on 24 apr 1999 (right). The arrows mark a toroidal structure.

The compact bright source in the central part of the bipolar outflow is a nozzle. The bipolar outflow is ejected from the nozzle at PA $= -44°$. The nearest part of the flow has a size not exceeding 0.05×0.15 AU, and its brightness temperature reaches $T_b \sim 10^{13}$ K. The velocity of the injector is V = 7.63 km/s. The maser emission of the structure is linearly polarized, see Fig. 3. The length and orientation of the lines correspond to the degree of polarization and orientation of the polarization plane. Also shown here on an enlarged scale are the bullet and the bipolar outflow with an angular resolution of 0.3 mas. The polarization of the emission from the bipolar outflow near the nozzle is 33 % and increases with distance to 50 %. This may be attributable to partial saturation of the amplification in the region of the nozzle, whose brightness temperature is an order of magnitude higher than that of the bipolar outflow (Matveyenko, Diamond & Graham 1998). As previously, bullets are observed within the active region.

4. High activity – epoch 1998-1999

In the period under consideration, the line had a Gaussian profile with linewidth $\sim$ 0.5 km/s, its velocity V = 7.65 km/s was conserved. The maser emission in February 1998 began to exponentially increase and reached its maximum level of F = 4.3 MJy in August – October. The emission began to exponentially decrease in November and reached its original level in May 1999. The structure of the active region remained almost the same as it was at the epoch 1995.6. Figure 4 shows the structure of the active region on October 14, 1998 and April 24, 1999. The bipolar outflow is highly collimated and is 5 x 0.2 AU in size (Fig. 4, left). The brightness temperatures of the bipolar outflow and the nozzle rose to $T_b \sim 10^{15}$ K and $T_b \sim 5 \times 10^{16}$ K, respectively.

Analysis of the parameters of the structure for the entire period of activity 1998-1999 showed that the relative line of sight velocities of the flows are $V_{NW} = --0.3$ km/s and $V_{SE} = 0.3$ km/s. In the plane of the sky the outflow velocities were $V_{NW} = 10$ km/s and $V_{SE} = 8$ km/s in the beginning of activity. They reached $V_{NW} = 6.8$ km/s and $V_{SE} =$ 5.0 km/s at the peak and then decreased to $V_{NW} = 4.0$ km/s and $V_{SE} = 3.5$ km/s in the period of activity decline. Thus, the high and low velocities precede the high activity and the decline in emission, respectively. The observed correlation of the supermaser emission with the flow velocity suggests collisional pumping, the interaction of the flow with the ambient medium.

The bipolar outflow has a helix structure that is determined by the precession of the rotation axis of the nozzle; the precession period is T $\simeq$ 10 yr, and the precession angle is $\simeq$ 16° (Matveyenko, Zakharin & Diamond 2004; Matveyenko, Demichev & Sivakon 2005).

A toroidal structure was discovered around nozzle at the end of the period of high activity. The torus is 0.6 AU in diameter, and its brightness temperature reaches $T_b \sim 10^{13}$ K. The plane of the torus is oriented perpendicular to the nozzle axis. (Fig.4, right). Probably the torus was present earlier, but its emission was blended with the supermaser. The dynamic range of the measurements was not enough to reveal a structure of relatively low brightness.

5. Bullets

Bullets are observed mostly in periods of low emission, when the disk-jet structure has a low brighness temperature. A first bullet was discovered after the first period of activity in 1988-1989 on a distance of 30 AU from the center of the accretion disk. The bullet had an elongated shape, reaching 6 AU in size. Its brightness temperature was $T_b \sim 10^{13}$ K (Fig. 2, 5) and its line of sight velocity relative to the nozzle was V $= -0.46$ km/s.

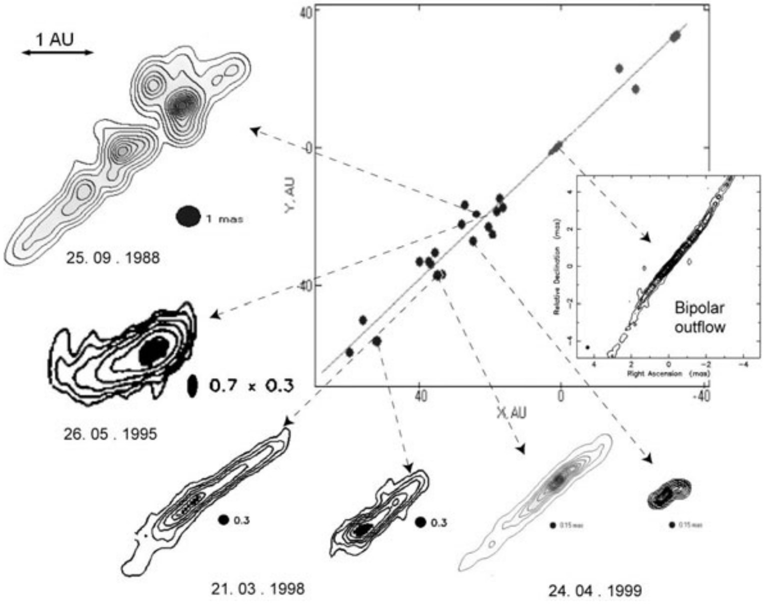

Figure 5. Structure of active region: bullets and outflow at different epoch.

Two bullets were observed during the quescent period of 1995. The brightness temperature of the bullets was $T_b \sim 10^{12}$ K. The southeastern bullet is at a distance of 18.5 AU from the nozzle in the direction PA $= 132°$. It has a comet-like (headtail) shape, and its line of sight velocity is $V_{SE} = 0.32$ km/s. However, the head is behind its tail. The northwestern bullet is at a distance of 32.5 AU from the nozzle in the direction PA

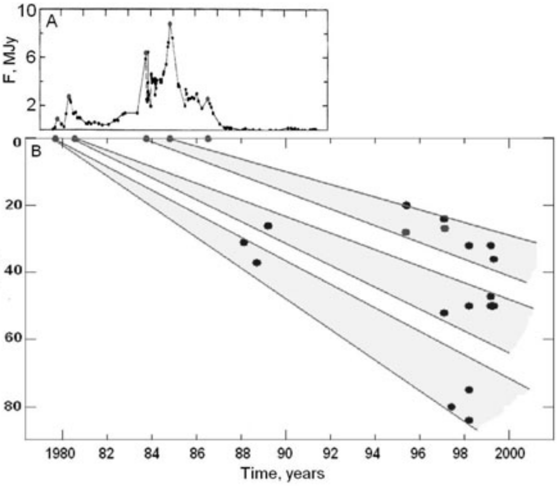

Figure 6. Maser flux distribution during the first active period (Abraham, Vilas Boas & del Ciampo 1981) (up) and bullets movement (down).

= 54°. Its velocity is V_{NW} = 0.18 km/s. The polarization of the emission from the southeastern bullet reaches 45% and 13 % from the northwestern bullet.

During the second active period 1998-1999 bullets were observed many times. In March 1998 two bullets were observed on distances of 47 AU and 68 AU, and heads were in front of the tails (Fig.5). In March – August 1999 were another two bullets in SE direction, on distances of 35 AU and 50 AU. Their size was 0.5×0.15 AU for the close compact bullet, and 2×0.15 AU for the distant elongated bullet. Brithness temperatures were $T_b \sim 10^{13}$ K, and $T_b \sim 5 \times 10^{13}$ K respectively. The overall bullet distribution in 1988-1999 is concentrated in a narrow cone ~ 10° orientated at PA = -44°, that corresponds to the nozzle of the bipolar outflow (Fig.5). Bullets are observed on distances up to 80 AU and are prevailing in the SE direction. The size of the bullets is 1-5 AU in length and 0.2 AU in width. The head of the bullets are located either before or after the tail. Bullets are oriented in the direction of the nozzle. The observed range of the line of sight velocity is within $-0.5 \leqslant V \leqslant 0.5$ km/s. In both the NW and SE directions bullets can have different velocity signs, which are determined by the angle of ejection. The cone of bullets is thus oriented within a few degrees of the plane of sky. It is possible to estimate the velocities of the bullets in the plane of sky $V_{sky} = V/sin(\phi/2)$, $\phi = 10°$, so $V_{sky} \geqslant$ 6 km/s. Bullets have a short visibility time, fading beyond the detection limit of $T_b \sim 10^{11}$ K within a few months.

6. Interpretation of the results

The observed highly organized structure, a chain of bright compact features distributed along the elongated S-shaped structure, corresponds to an accretion disk separated into rings seen edge-on. The disk is 27 AU in diameter and 0.3 AU in thickness. The observed velocity−distance dependence of the components (the rings) corresponds to a rigid-body rotation, $V_{rot} = \Omega R$. The angular velocity Ω corresponds to a rotation period of the disk T = 170 yrs. The maser radiation is concentrated in the azimuthal plane of the rings; its directivity reaches 10^{-3}. The decrease of the rotation velocity towards the center of disk is determined by the transfer of its kinetic energy to the bipolar flow. The energy transfer

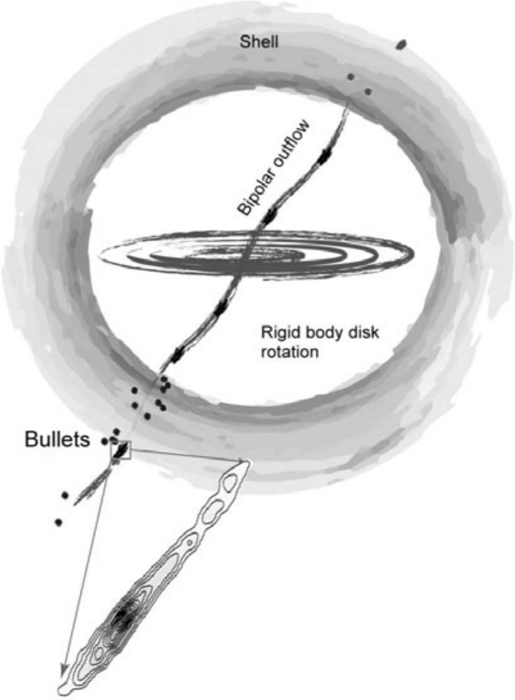

Figure 7. Model of H_2O supermaser in Orion.

causes the decrease of the Keplerian velocity $V^2R = MG$ to the observed rigid-body limit.

The diameter of the outflow on the exit of the nozzle does not exceed 0.05 AU. The outflow is higly collimated, spreading much farther than its visible size up to 80 AU (Fig. 7). Dense fragments of the outflow are visible as bullets. The precession of the nozzle axis produces the conical helix shape of the outflow. The period of precession is T=10 years.

Outflow, bullets and the surronding medium contain ice granules, which become sublimated and produce H_2O molecules. The velocity of compact knots in the outlflow is $\sim 4 - 10$ km/s. The interaction of H_2O molecules with the surrounding medium produces collisional pumping of the maser.

The analysis of bullets movement show that they were ejected during the first period of activity in 1979-1987 (Fig. 6). The ejection is accompanied by powerful supermaser outbursts.

The emission of the structure is amplified in the surrounding medium – shell at V = 7.65 km/s in a 0.5 km/s band by more than two orders of magnitude. This increases the brightness temperatures to the supermaser level of 10^{17} K.

7. Conclusion

Our studies of the superfine structure of one of the active star formation regions in Orion KL in H_2O maser emission have shown the following:

Intense H_2O maser emission accompanies the formation of a thin accretion disk, a highly collimated bipolar outflow, and an envelope (Fig. 7).

The disk is 27 AU in diameter and 0.3 AU in thickness. The disk is separated into rings containing ice granules. Radiation and stellar wind sublimate and blow away the water molecules to form haloes around the rings. The radiation of the maser ring is concentrated in the azimuthal plane and has a high directivity, $\leqslant 10^{-3}$.

The central part of the disk is 15 AU in diameter and rotates as a rigid body; the rotation period is T = 170 yrs. The kinetic energy of the accreting matter and the disk is transferred to the bipolar outflow, causing a deviation from Keplerian motion.

The nozzle is surrounded by a toroidal structure 0.6 AU in diameter. The diameter of the ejected flow is ~ 0.05 AU. The flow velocity during the active period reaches 10 km/s.

The highly collimated bipolar outflow is ~0.2 AU in thickness and ~5 AU in apparent length and has a conical helix structure determined by precession. The precession period is ~10 yr, and the precession angle is 16°.

Compact ejections-bullets are observed on distances up to 80 AU. They are dense fragments of the bipolar outflow. Bullets visible in 1988-1999 were ejected during the first period of activity in 1979-1987.

The surrounding medium-shell amplifies the emission at V = 7.65 km/s in a 0.5 km/s band by more than two orders of magnitude, which determines the supermaser emission.

The maser emission has a high degree of linear polarization determined by the pumping directivity.

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