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Investigation of the OH and H_2O Maser Emission from the Semiregular Variable HU Puppis

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Abstract—We present the results of our monitoring of the semiregular variable HU Pup in the 1612, 1665, and 1667-MHz OH lines and the 22.235-GHz H_2O line. The maser emission in the 1612-MHz satellite line has been detected from this source for the first time. Strong variability of the emission has been observed in all three OH lines, including the radial-velocity drift of the two most intense features. Zeeman splitting components have been found. The longitudinal magnetic field strength has been estimated to be 1.0, 1.6 and 2.7, 3.2 mG in the 1665 and 1667-MHz lines, respectively. Our OH and H_2O observations have revealed fairly stable structures in the masing region and have allowed us to estimate the variability period of the maser emission ($\sim$1.5 yr). A possible model of the maser source in HU Pup is discussed.

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INTRODUCTION

Many of the long-period variable stars are strong sources of maser radio emission in the molecular lines of hydroxyl (OH) at 18 cm and water vapor at 1.35 cm.

Owing to the Λ-doubling effect and the presence of a hyperfine structure, the ground rotational level of hydroxyl $^2\Pi_{3/2}$, $J = 3/2$ is split into four sublevels between which four permitted electric dipole transitions with frequencies of 1612, 1665, 1667, and 1720 MHz are possible. For the Boltzmann distribution of molecules in sublevels, the line intensity ratio is $1:5:9:1$. In the OH masers associated with late-type stars (especially with OH/IR stars), the 1612-MHz satellite line often turns out to be the strongest one. Its intensity can exceed the intensity of the main lines. The 1720-MHz OH satellite line (IIa OH masers) is never observed in circumstellar masers.

HU Pup (CD-28 5095, IRAS 07536−2830, IRC-30105, ASAS 075540−2838.9) is an SRa semiregular variable star of spectral type M3. According to the GCVS data (Kholopov et al. 1987), the variability cycle of the star is $238^{\rm d}$. However, more recent observations (2001—2009) showed that the variability period is considerably longer and varies within the range 1—2.2 yr (the All-Sky Automated Survey data, http://www.astrouw.edu.pl/asas/, Pojmański 2003). The intervals between the strongest maxima are about 2 yr. The V brightness is $11.5^{\rm m}$ at maximum and $13.2^{\rm m}$ at minimum. HU Pup is a source of OH, H_2O, and SiO maser emission. The distance to HU Pup is estimated to be 0.52 kpc (Szymczak and Le Squeren 1999).

The hydroxyl maser emission in HU Pup was detected in the 1667-MHz line on August 29, 1986 (Le Squeren et al. 1992). The observations performed in 1990 (Szymczak et al. 1995) revealed new emission features: at 1665 and 1667 MHz in right- and left-hand circular polarizations, respectively. No double-peaked structure of the spectra typical of class OH/IR objects was observed. The observations of various authors in 1984—1987 revealed no 1612-MHz line emission from HU Pup.

The H_2O and SiO maser emission in HU Pup was detected in 1987 (Deguchi et al. 1989) and 1989 (Haikala et al. 1994). It is observed in very close radial velocity ranges, 40—50 km s^{-1}, while the OH emission is in a different velocity range, 30—40 km s^{-1}.

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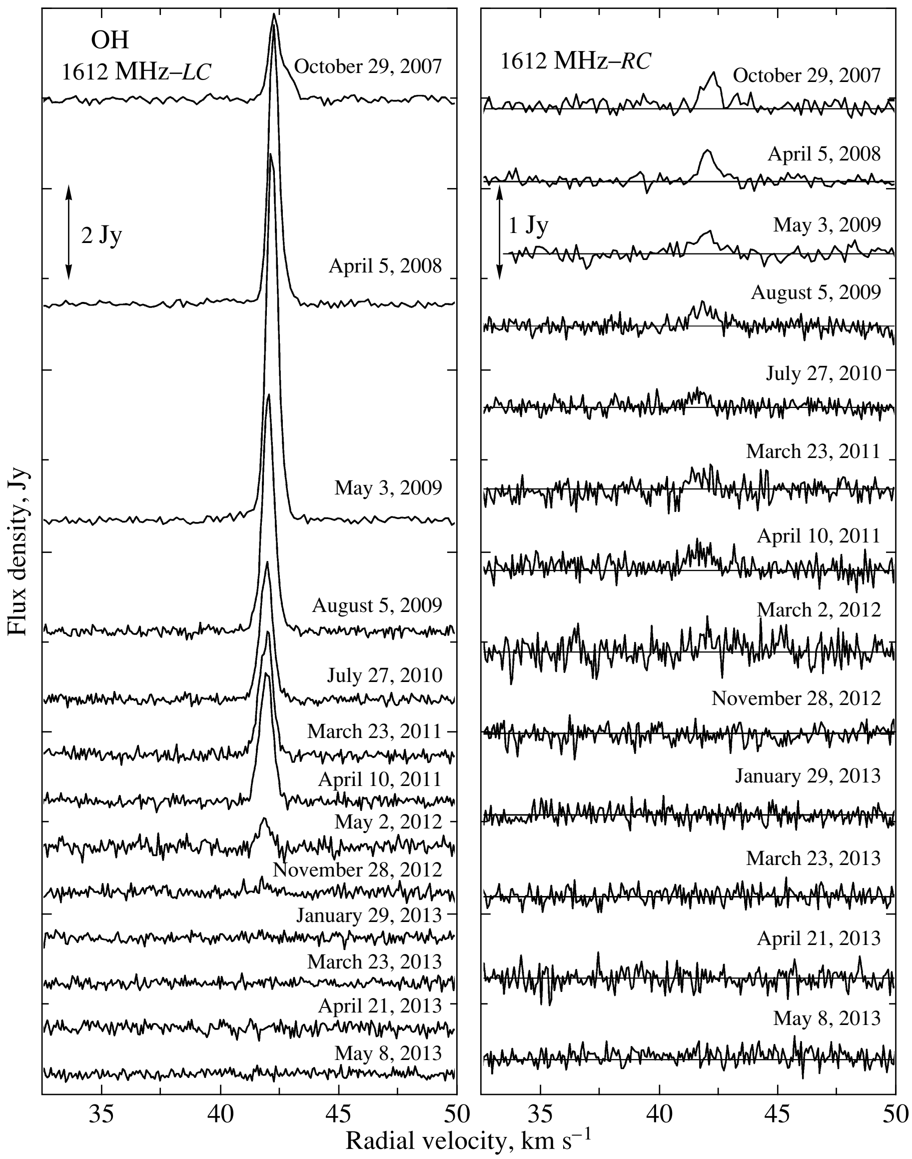

Fig. 1. Spectra of the OH maser emission from HU Pup in the 1612-MHz line in left- and right-hand circular polarizations at various epochs. The radial velocity relative to the local standard of rest is along the horizontal axis and the flux density is along the vertical axis. The double arrow indicates the scale division value.

No CO line emission was detected; only an upper limit was estimated (see, e.g., Deguchi et al. 1990).

OBSERVATIONS AND RESULTS

We have monitored the maser emission from HU Pup at various epochs in the lines of two molecules: hydroxyl at 18 cm and water vapor at 1.35 cm. The observations in the 1612, 1665, and 1667-MHz OH lines were performed at the radio telescope of the Paris–Meudon Observatory in Nançay (France). At declination $\delta = 0°$, the telescope's beamwidth at 18 cm is $3.5' \times 19'$ in right ascension and declination, respectively. The telescope's sensitivity for $\lambda = 18$ cm and $\delta = 0°$ is 1.4 Jy K^{-1}. The system noise temperature ranges from 35 to 60 K, depending on the observing conditions. The spectrum analysis was carried out by an autocorrelation spectrum analyzer with a radial velocity resolution in the main OH lines of 0.068 km s^{-1} (0.137 km s^{-1} in 2009). The emission was recorded in linear (with position angles of 0°, 90°, and ±45°) and circular (right- and left-hand) polarizations, which allowed all Stokes parameters to be obtained. The instrumentation and the observing and data processing technique were described in detail previously (Slysh et al. 2010; Rudnitskii et al. 2010; Lekht et al. 2012). An overview of our observations of circumstellar OH

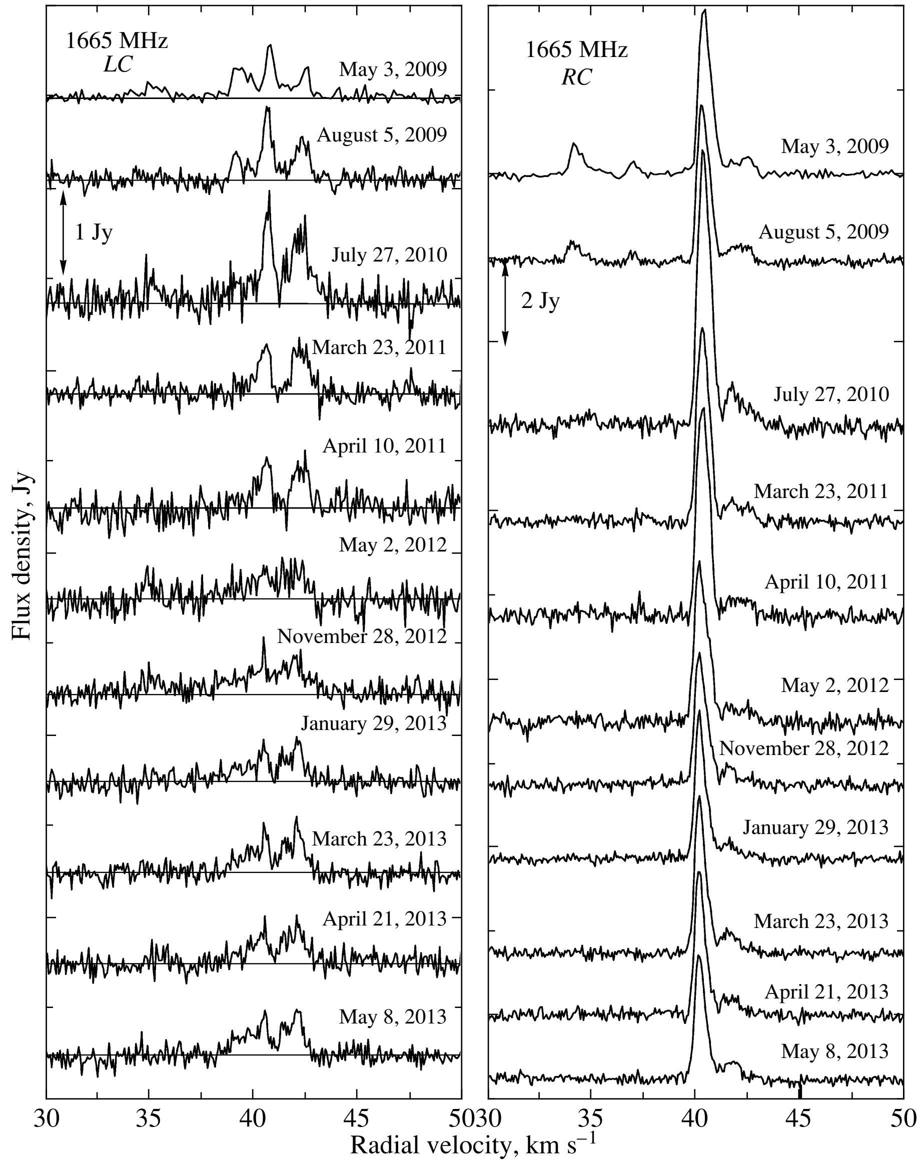

Fig. 2. Same as Fig. 1 for the 1665-MHz OH line.

masers in 2007–2009 is given in Rudnitskii et al. (2010).

The observations of the H_2O maser emission in the 1.35-cm line were carried out at the RT-22 radio telescope of the Pushchino Radio Astronomy Observatory (Lekht et al. 2009). The telescope's beamwidth is 2.6′ and the system noise temperature is 120–300 K, depending on the weather conditions. The signal was analyzed by a 2048-channel autocorrelation spectrometer with a radial velocity resolution at 22 GHz of 0.0822 km s^{-1}. The antenna sensitivity is 25 Jy K^{-1}.

Figures 1–3 present the spectra of the hydroxyl maser emission in the 1612, 1665, and 1667-MHz lines in left- and right-hand circular polarizations at various epochs. The radial velocity relative to the local standard of rest in km s^{-1} is along the horizontal axis and the flux density in Janskys is along the vertical axis. The double arrow indicates the scale division value.

Figure 4 shows the Stokes parameters for the OH emission in the 1612, 1665, and 1667-MHz lines for the epoch of August 5, 2009. The time variations of the Stokes V parameter for all three lines are shown in Fig. 5. In the spectra of the 1665 and 1667-MHz lines, we detected the pairs of features that arose from the emission line splitting into two components in the longitudinal magnetic field (Zeeman splitting). The components are shifted toward higher and lower velocities relative to the line center and have opposite signs of the elliptical polarization. The cases

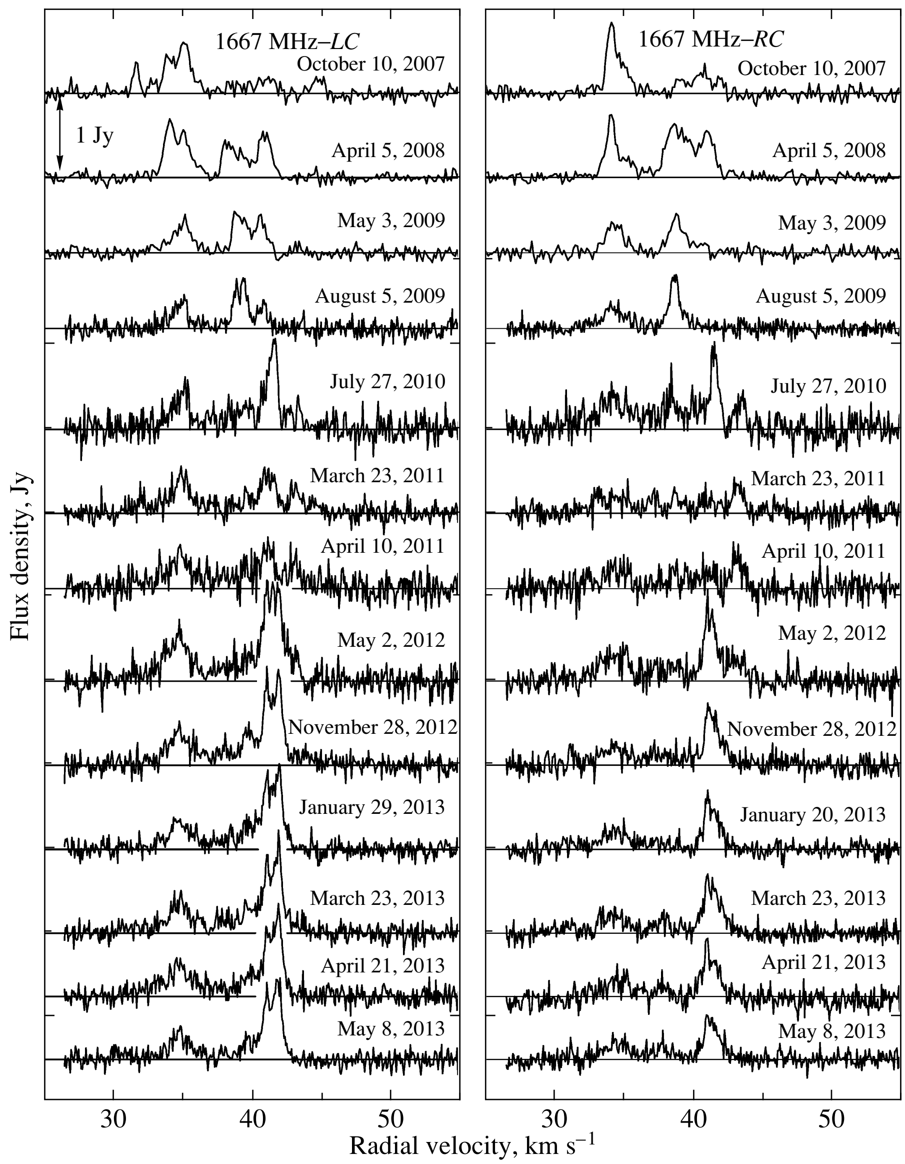

Fig. 3. Same as Fig. 1 for the 1667-MHz OH line.

where one of the Zeeman splitting components can supersede the other through maser beam instability are possible (Shklovskii 1969). In this case, only one 100% circularly polarized component is observed in the spectrum. The parameters of the components are given in the table.

Figure 6 presents the H_2O 1.35-cm spectra for various epochs. Regular observations (monitoring) have been carried out since January 2010. The emission was observed in the velocity range 40–50 km s^{-1}. Despite the large spectrum variations, the average spectra for the time intervals 2010–2011 and 2012–2013 differ insignificantly (Fig. 7). Their structure is well preserved. The most significant changes in the spectrum structure occurred only in the second half of 2013.

DISCUSSION

Hydroxyl

Prior to our observations, no emission in the 1612-MHz satellite line had been recorded. In

Magnetic field strengths in maser condensations in the envelope of HU Pup

Line, MHz	V_{LSR}, km s^{-1}	Feature number	Splitting, km s^{-1}	Magnetic field strength, mG
1665	39.7	1; 2	0.95	1.6
	41.9	3; 4	0.60	1.0
1667	34.7	5; 6	1.13	3.2
	39.0	7; 8	0.94	2.7

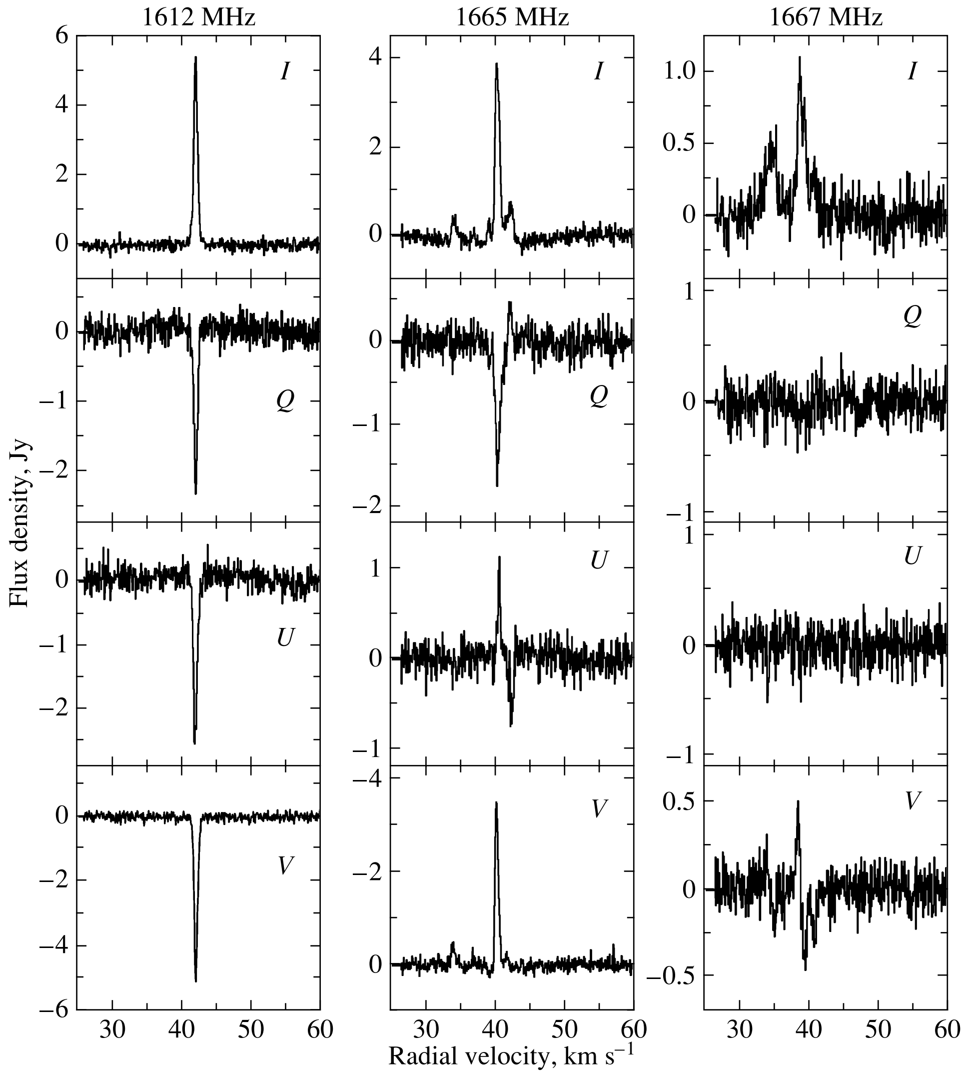

Fig. 4. Stokes parameters for the OH emission in the 1612, 1665, and 1667-MHz lines at the epoch of August 5, 2009.

October 2007, we detected this emission in both circular polarizations (Fig. 1), but not at the velocities at which it was observed previously in the main lines (Fig. 10). The emission in left-hand circular polarization at a velocity of 42.2 km s^{-1} was strongest. The emission peaked at the beginning of 2009. At the end of 2012, the emission disappeared.

In the 1665-MHz line, we observed the emission in a wider range of radial velocities (33–43 km s^{-1}) than it was known previously (32–38 km s^{-1}). The emission in right-hand circular polarization at a velocity of 40.2 km s^{-1} was most intense. The maximum was observed on July 27, 2010.

We observed the weakest OH emission in the 1667 MHz line. It was present in both circular polarizations and the velocity range was considerably wider (31–44 km s^{-1}) than before our observations.

For two most intense emission features (42.2 and 40.2 km s^{-1} in the 1612 and 1665-MHz lines, respectively), there was a drift of the emission in radial velocity at a mean rate of 0.103 and 0.054 (km s^{-1}) yr^{-1}.

Thus, our monitoring showed that the OH emission in HU Pup is highly variable in all three OH lines.

As a rule, the OH maser emission is strongly polarized. The degree of polarization can reach 100% (see Fig. 4). The Stokes V parameter is more informative. It allows us to reveal the Zeeman splitting components and to estimate the longitudinal magnetic field strength. We found four pairs of Zeeman splitting components (see Fig. 5), two in each main

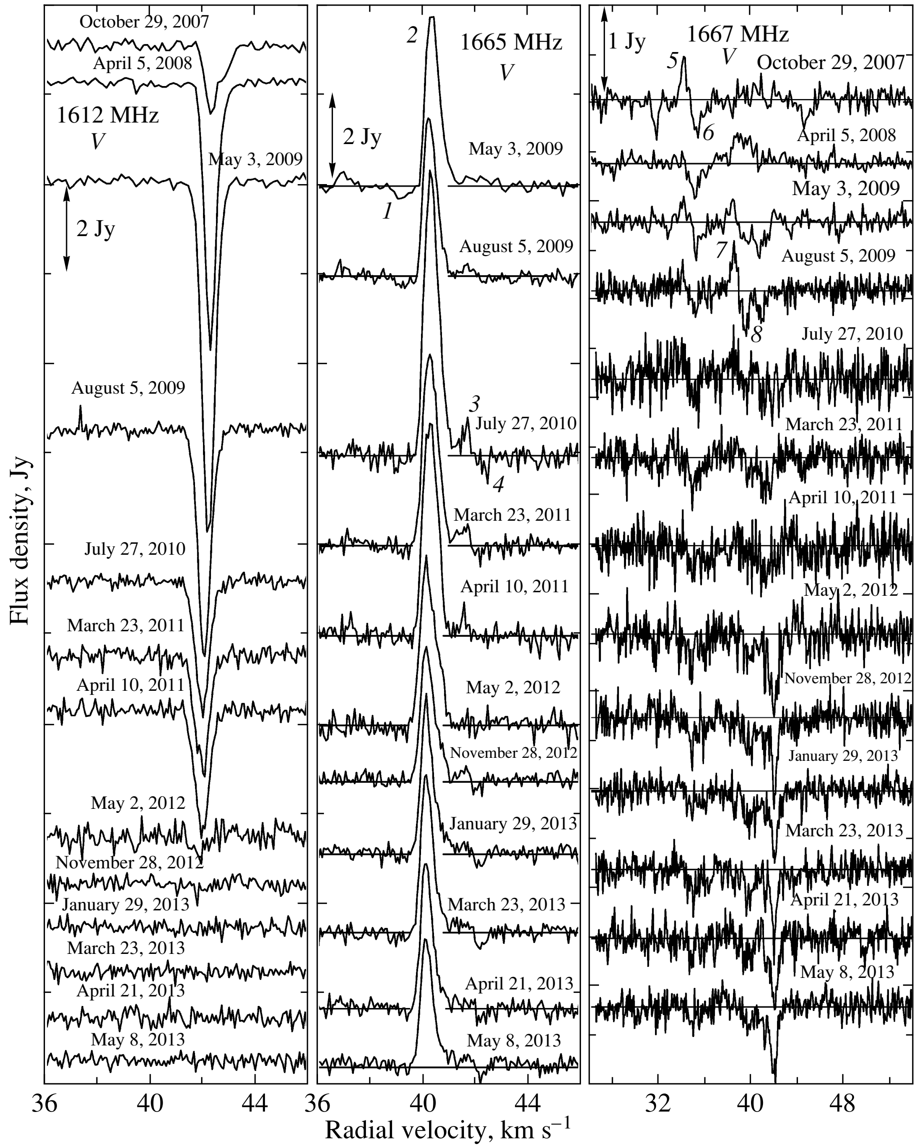

Fig. 5. Variability of the Stokes V parameter for the OH emission in the 1612, 1665, and 1667-MHz lines. The detected pairs of Zeeman splitting features are numbered.

line. The main parameters of the components are given in the table. The mean velocity of each pair, i.e., the velocity that the unsplit feature would have in the absence of a magnetic field, is given as V_{LSR}. It is important to note that, despite the velocity drift of the 42.2-km s^{-1} feature, its Zeeman splitting was retained. The mechanism of determining the Stokes parameters and the magnetic field from the Zeeman splitting is described in more detail in Rudnitskii et al. (2010).

The difference between the magnetic field estimates from the 1665 and 1667-MHz lines by a factor of $\sim$2.5 suggests that the hydroxyl masing regions are spatially separated.

Water Vapor

Despite the large variations, the main emission features are visible in most spectra. Moreover, comparison of our spectra for various epochs (Fig. 6) and the average spectra (Fig. 7) with the spectra obtained previously by other authors since the discovery of the H_2O emission in HU Pup reveals many common features, i.e., features at close radial velocities. The slight velocity difference can be caused by observations with different spectral resolutions and by small systematic errors. All of this suggests a fairly stable structure of the water-vapor masing region and the absence of noticeable turbulent motions.

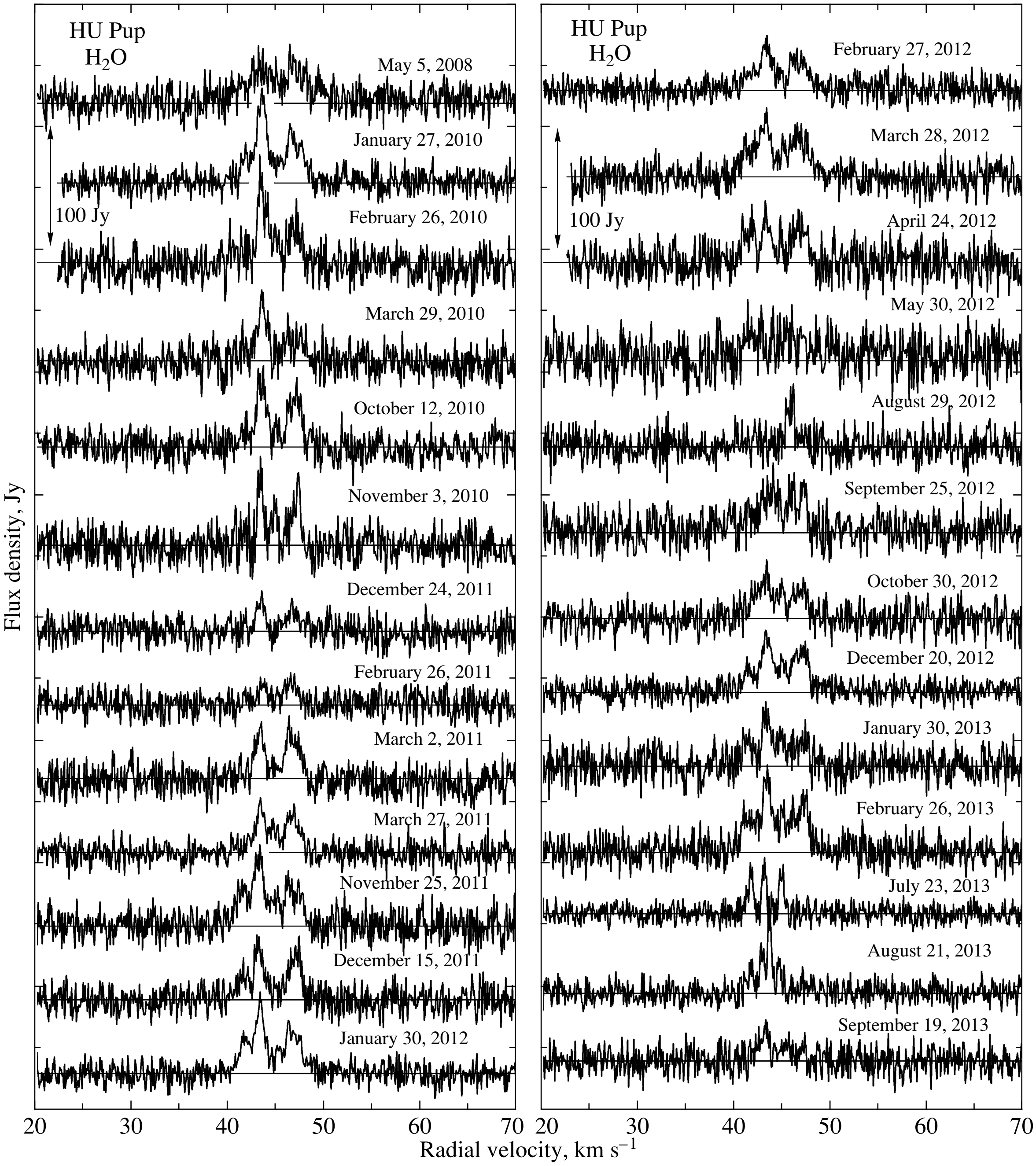

Fig. 6. Spectra of the H_2O maser emission ($\lambda = 1.35$ cm) at various epochs.

For three emission features (41.7, 43.4, and 47.5 km s^{-1}), there is a correlation between the flux variations. The variability can be caused by a nonstationary shock propagating from the star. For all three features, the variability periods determined from both maxima and minima are very close. The mean period is 1.5 yr.

Integrated Flux

Since the OH and H_2O maser emission turned out to be highly variable, it was possible to plot the emission variability. Figures 9a and 9b present the variability of the integrated flux (the sum of the emissions in left- and right-hand circular polarizations) in the 1612, 1665, and 1667-MHz OH lines and in the H_2O line, respectively. For H_2O, we also used the

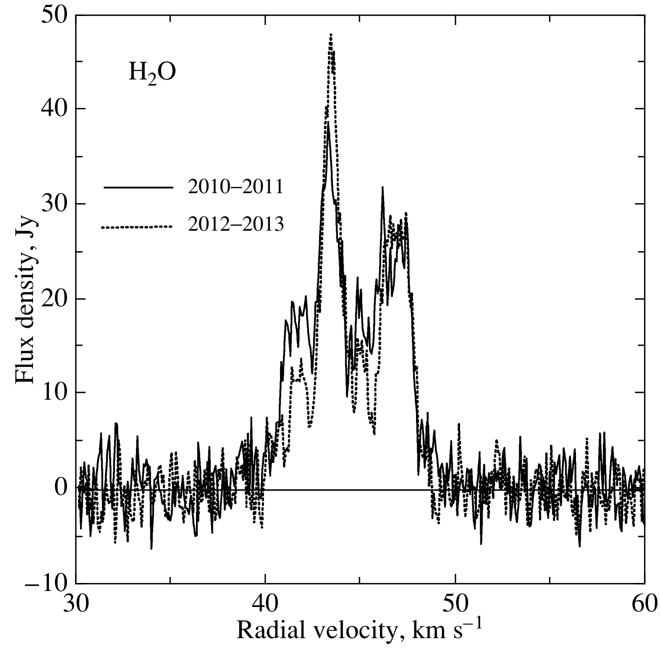

Fig. 7. Average H_2O emission spectra for the time intervals 2010–2011 (solid curve) and 2012–2013 (dotted curve).

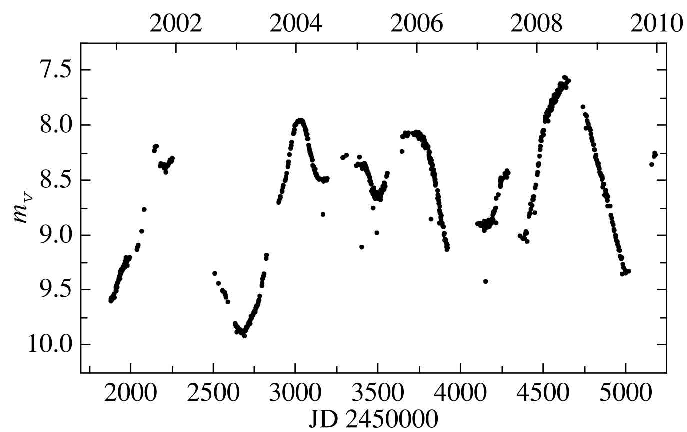

Fig. 8. V-band light curve of HU Pup from the ASAS data (Pojmański 2003).

data from Kim et al. (2010) for the epoch of June 7, 2009.

The emission maxima in the 1612 and 1665-MHz OH lines are well defined, but no periodicity is traceable in the time interval 2007–2013. On the other hand, three maxima are observed for H_2O, though the first of them is not well defined, because the number of observations is insufficient. The intervals are 1.85 and 1.08 yr between the maxima and 1.53 and 1.08 yr between the minima. In the 1667-MHz line, there are three maxima, but they are not so distinct as in other lines.

Thus, given the variability of individual emission features, the most probable period of the H_2O maser emission variability can be $\sim$1.5 yr. This value agrees well with the visual light curve of HU Pup (see Fig. 8).

Model

The SiO maser emission spectra show a double-peaked structure (see, e.g., Nyman et al. 1998; Kim et al. 2010). This means that we receive the emission both from the part of the stellar envelope nearest to us and from the distant one. The dip in the spectrum

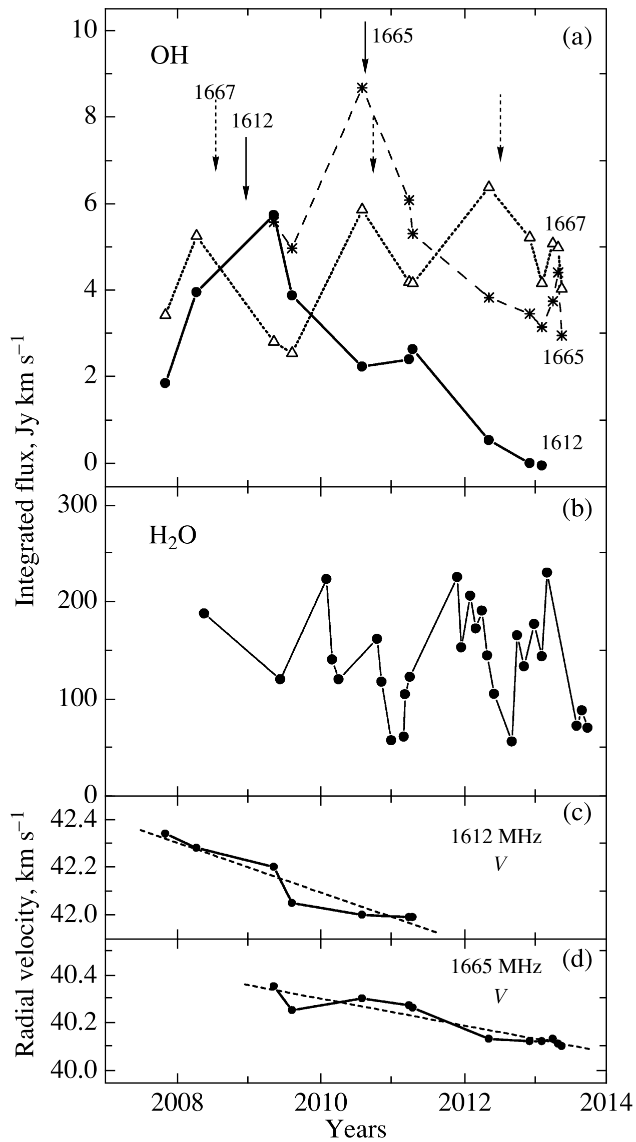

Fig. 9. Variability of the the integrated flux of the OH maser emission in the 1612, 1665, and 1667-MHz lines (a) and the 1.35-cm H_2O line (b); the radial velocity drift of the maximum of Stokes V parameter for the emission in the 1665 (c) and 1667-MHz (d) lines. The dashed straight lines are the fits to the observed drift.

determines the stellar velocity; it is $V_{LSR} \approx 46$ km s^{-1} for HU Pup. The double-peaked structure of the spectra is also traceable for the H_2O emission with a dip at a velocity of about 45–46 km s^{-1} (see also Szymczak and Engels 1995). Thus, 46 km s^{-1} can be taken as the velocity of the star HU Pup relative to the local standard of rest.

We pointed out that the hydroxyl maser emission in all lines occurred at lower radial velocities than the H_2O and SiO emission, i.e., at $V_{LSR} < 46$ km s^{-1}. This is possible when the OH masing region is associated with the part of the envelope nearest to the observer. This conclusion is confirmed by all observations of HU Pup, according to which the OH spectra have no double-peaked structure. In this case the observed drift of two emission features toward lower radial velocities is explained by an accelerated motion of this part of the envelope relative to the star.

Let us return to the visual light curve (see Fig. 8). The nearest maximum that precedes the OH and H_2O emission maxima is the visual maximum at epoch 2008.5.

Since the hydroxyl maser pumping is radiative, the delay between the hydroxyl maxima and visual maxima will be small, in spite of the fact that the OH masing regions are fairly far from the star. We cannot estimate the delay with a good accuracy because of the insufficient number of observations in 2008 (see Fig. 9) and, therefore, we cannot estimate the distance from the star HU Pup to the OH maser emission region with a good accuracy.

The water-vapor maser emission region is much closer to the star. Since the pumping is collisional, the H_2O emission maximum is delayed relative to the visual maximum by a larger value than that for the hydroxyl maser. According to our observations, the delay is about 1.5 yr, corresponding to a distance of the water-vapor masing region from the star of $\sim 10^{14}$ cm. For this estimate, we adopted a shock velocity of ~ 15 km s^{-1}, typical of the envelopes of late-type variable stars (see, e.g., Richter et al. 2003).

MAIN RESULTS

Let us list the most important results of this paper.

—The OH maser emission in the 1612-MHz satellite line was detected. The emission peaked at the beginning of 2012.

—There is a drift of the 1612 and 1665-MHz emission toward lower radial velocities.

—The Zeeman splitting components were found. The longitudinal magnetic field strength was estimated to be 1.0, 1.6 and 2.7, 3.2 mG in the 1665 and 1667-MHz lines, respectively.

—The variability period of the maser emission, both OH and H_2O, was determined from the variability of the integrated flux and the fluxes of individual emission features. The mean period is ~ 1.5 yr. This is consistent with the visual light curve.

—The star's velocity relative to the local standard of rest was estimated from the dips in the H_2O and SiO spectra to be 46 km s^{-1}.

—The distance from the star to the masing regions was estimated from the delays of the H_2O and OH maser emission maxima to be $\sim 10^{14}$ cm.

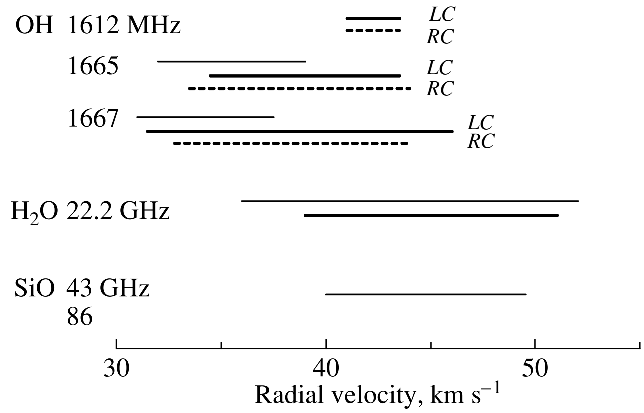

Fig. 10. Schematic view of the radial velocity ranges for the emission in the 1612, 1665, and 1667-MHz OH lines, the 22-GHz H_2O line, and the 43 and 86-GHz SiO lines for left- (LC) and right-hand (RC) circular polarizations of OH. The thin lines indicate the emission ranges obtained prior to our observations.

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REFERENCES

1. S. Deguchi, Y. Nakada, and J. R. Forster, Mon. Not. R. Astron. Soc. **239**, 825 (1989).
2. S. Deguchi, Y. Nakada, and R. Sahai, Astron. Astrophys. **230**, 339 (1990).
3. L. K. Haikala, L.-Å. Nyman, and V. Forsström, Astron. Astrophys. Suppl. Ser. **103**, 107 (1994).
4. P. N. Kholopov, N. N. Samus', M. S. Frolov, et al., *General Catalog of Variable Stars,* 4th ed. (Nauka, Moscow, 1987) [in Russian].
5. J. Kim, S.-H. Cuo, C. S. Oh, and Do-Y. Byun, Astrophys. J. Suppl. Ser. **188**, 209 (2010).
6. E. E. Lekht, A. M. Tolmachev, and G. M. Rudnitskij, Astron. Lett. **35**, 132 (2009).
7. E. E. Lekht, M. I. Pashchenko, and G. M. Rudnitskii, Astron. Rep. **56**, 45 (2010).
8. L.-Å. Nyman, P. J. Hall, and H. Olofsson, Astron. Astrophys. Suppl. Ser. **127**, 185 (1998).
9. G. Pojmański, Acta Astron. **53**, 341 (2003).
10. He. Richter, P. R. Wood, P. Woitke, et al., Astron. Astrophys. **400**, 319 (2003).
11. G. M. Rudnitskii, M. I. Pashchenko, and P. Colom, Astron. Rep. **54**, 400 (2010).
12. I. S. Shklovskii, Sov. Astron. **13**, 1 (1969).
13. V. I. Slysh, M. I. Pashchenko, G. M. Rudnitskii, V. M. Vitrishchak, and P. Colom, Astron. Rep. **54**, 599 (2010).
14. A. M. le Squeren, P. Sivagnanam, M. Dennefeld, and P. David, Astron. Astrophys. **148**, 133 (1992).
15. M. Szymczak and A. M. le Squeren, Mon. Not. R. Astron. Soc. **304**, 415 (1999).
16. M. Szymczak and D. Engels, Astron. Astrophys. **296**, 727 (1995).
17. M. Szymczak, A. M. Le Squeren, P. Sivagnaman, et al., Astron. Astrophys. **297**, 424 (1995).

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