Physics of Magnetic Stars, 2007, pp. 262–270

Line profile variability and the possible magnetic field in the spectra of supergiant ρ Leo

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1 Introduction

Line profiles in spectra of OB stars are usually strongly variable (Morel et al. 1998). One can detect both the stochastic line profile variability (lpv) connected with formation of the small-scale structures in the stellar wind (Eversberg et al. 1998, Kholtygin et al. 2003) and the regular lpv, induced by the large-scale structures in the wind (de Jong et al. 2001). The regular line profile variability are often connected with the co-rotation of the large-scale structures in the wind (Kaper et al. 1999).

The latter might be explained by accepting the hypothesis that hot stars possess global magnetic fields (Neiner 2002, Donati et al. 2002). Magnetic field can also regularize the wind structures induced by stellar non-radial pulsations (Owocki and Cranmer 1988). The recent measurements have shown that only two O stars and a small part of B stars possibly have magnetic fields (e.g. Donati et al. 2001, Donati et al. 2002, Henrichs et al. 2003).

So, the problem of searching for the magnetic field of O and early B stars is still actual. Recently we have proposed (Kholtygin et al. 2004) the program of searching for weak magnetic field of OB stars with the aim to know if the magnetic field is the common feature of all OB stars or not. In the present paper we report the results of searching for magnetic field of the B1I supergiant ρ Leo.

2 Main information about ρ Leo. Observations and data reduction

The supergiant ρ Leo (HD 91316) is a slowly rotating ($V \sin i = 75$ km/s) star of spectral class B1Ib. The effective temperature of the star $T_{\rm eff}$ is very uncertain. In the paper by Morel et al. (2004) a value of $T_{\rm eff} = 20260$ K was given, but according to SteLib $T_{\rm eff} = 24200$ K, $\lg(g) = 3.09$. On the HR Diagram ρ Leo is located near the β Cep star instability domain (see, for example, Pamyatnykh 1999).

Parameters of the star are given in Table 1. In the table
$T_{\rm eff}$ — effective temperature of the star,
M — mass of the main component of the system,
$\dot{M}$ — mass loss rate,
L — bolometric velocity,
V_∞ — terminal velocity of stellar wind,
Vsin i — rotation velocity of the star.

The observations were made in 2004–2005. In 2004 the star was observed in the Special Astrophysical Observatory (SAO) with using the 6-m telescope (Kholtygin et al. 2006c, spectrograph NES) and also in Bohyunsan Optical Astronomy Observatory (BOAO) at the 1.8-m telescope with

Table 1: Parameters of the star ρ Leo

Parameter	Value	References
$T_{\rm eff}$,	24200	SteLib
$M/M_{\odot}$	22	Morel et al. (2004)
$M/M_{\odot}$	32	Morel et al. (2004)
V_{∞}	1110	Howarth et al. (1997)
$-\lg \frac{\dot{M}}{M_{\odot}}$	-6.20	Morel et al. (2004)
$\lg L/L_{\odot}$	5.18	Morel et al. (2004)
Vsin i (km/s)	75	Howarth et al. (1997)

the BOES spectrograph. In 2005 spectra of the program star were obtained at the 6-m telescope of SAO with the NES and MSS spectrographs. The log of observations is given in Table 2.

Table 2: Observation of ρ Leo in 2004-2005

Number of spectra	Exposition (min)	Full time of observations	Telescope	Spectrograph, CCD
		Jan 10/11 2004		
30	6	3.5	SAO[1], 6-m	NES[2], 2kx2k
7	9/10	0.6	BO, 1.8 m	BOES, 2kx2k
		Jan 14/15 2004		
11	4	2.5	BO, 1.8 m	BOES, 2kx4k
		Feb 3/5 2004		
15	4/7	3.0	BO, 1.8 m	BOES, 2kx4k
		Jan 30/31 2005		
8	4	0.5	SAO, 6-m	MSS[3], 2kx2k
		Feb 22/23 2005		
2	20	1.0	SAO, 6-m	NES, 2kx2k
		Feb 23/24 2005		
2	20	1.0	SAO, 6-m	NES, 2kx2k

Comments: [1]Special Astrophysical Observatory in the Northern Caucasus, Russia
[2]Echelle spectrograph in the Nasmyth focus of the 6-meter telescope of SAO
[3]Main Stellar spectrograph in the Nasmyth focus

Spectral observation in SAO on January 10/11 2004 were made in the region $\lambda\lambda\,4500-6000\,\text{Å}$ with using a quartz echelle spectrograph NES in Nasmyth focus (Panchuk 2002) with 2048×2048 Uppsala CCD.

The reduction of SAO spectra was made with using the MIDAS package (eg., Kholtygin et al. 2003). For finding the positions of the spectral order the method of Ballester (1994) was employed. For studying lpv, spectra was normalized to the individual continuum for each spectral order. The method of Shergin (1996) was used for determining the continuum level.

Part of the spectra was obtained at BOAO 1.8-m telescope on January 11, 14, 15 and February 3/5, 2004 with the fiber-fed echelle spectrograph BOES (BOES) with a large CCD (2048×4096 pixels, 15×15 $\mu\mu$ per pixel). All 17 spectra in BOAO were obtained in the $3782\,\text{Å} \le \lambda \le 9803\,\text{Å}$ region. Preliminary reduction of CCD frames was fulfilled with the help of IRAF. The next processing steps were made with using the modified version (Dech20T) of the Dech package (Galazutdinov, 1992)). All BOAO spectra were normalized to the continuum level. The procedure of finding the continuum level has recently been described by us (Kholtygin et al. 2006a).

Observations in SAO in 2005 were made both with the NES spectrograph and with the main stellar spectrograph (MSS). Observations were fulfilled with a new polarization analyzer described by Chountonov (2004). Then analyzer consists of an achromatic waveplate, which can be rotated and take 2 positions (0^o and 45^o), a diaphragm of 5 arcsec, a dichroic polarizer, a double slicer and a slit. The double slicers in the new analyzer is used to increase the efficiency of measurements. The number of strips is 14 (7 strips per each polarization). The light from a star passes through the liquid crystal modulator, which can be in two states to create phase shifts of 0^o and 180^o.

The procedure of reduction for spectra obtained in 2005 is also described by Chountonov (2004). All spectra was normalized to the continuum level. The quality of spectra appeared to be very good with a signal-to-noise ratio of up to 2100.

3 Line profile variations

Night mean line profiles in spectra of OB stars show significant variations (de Jong et al. 2001). For example in Fig. 1 we plot part of the spectra of ρ Leo in the wavelengths interval $\lambda\lambda$ 5650–5720 Å in comparison with the mean over all the spectra of ρ Leo that we obtained in 2004 (see Table 2).

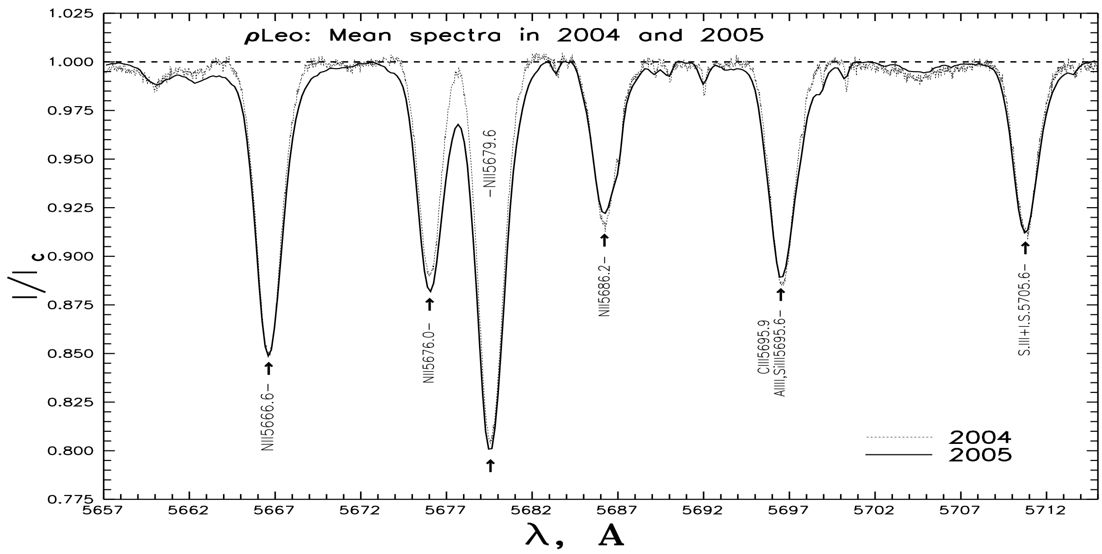

Figure 1: Mean spectra of ρ Leo obtained in 2004 and 2005.

In the figure we can see that the amplitude of the lpv in spectra of ρ Leo is about of 1-2% in the continuum units. Night mean profiles obtained for ρ Leo in SAO and BOAO on January 11, 2004 practically coincide (Kholtygin et al. 2006c). That is evidence of the good internal quality of the procedures we used for drawing the continuum level.

3.1 The regular line profile variability in spectra of ρ Leo

To illustrate the lpv in spectra of ρ Leo, we plot different line profiles for 30 spectra obtained on January 10/11, 2004 in SAO together with the night mean spectrum in Fig. 2.

One can see that the lpv occurs only in the limits of the line profiles and there is no lpv out of the lines. The Clean analysis of the lpv in spectra of ρ Leo reveal 8 regular components in the frequency region $0.14 \le \nu \le 6.2\,\mathrm{d}^{-1}$ with periods from 6.2^h to 7.3^d (Kholtygin et al. 2006c). These regular components are connected with non-radial pulsations and the rotational modulation of the line profiles. The slowest of the components with a period of 7.3^d is probably the rotational period of the star.

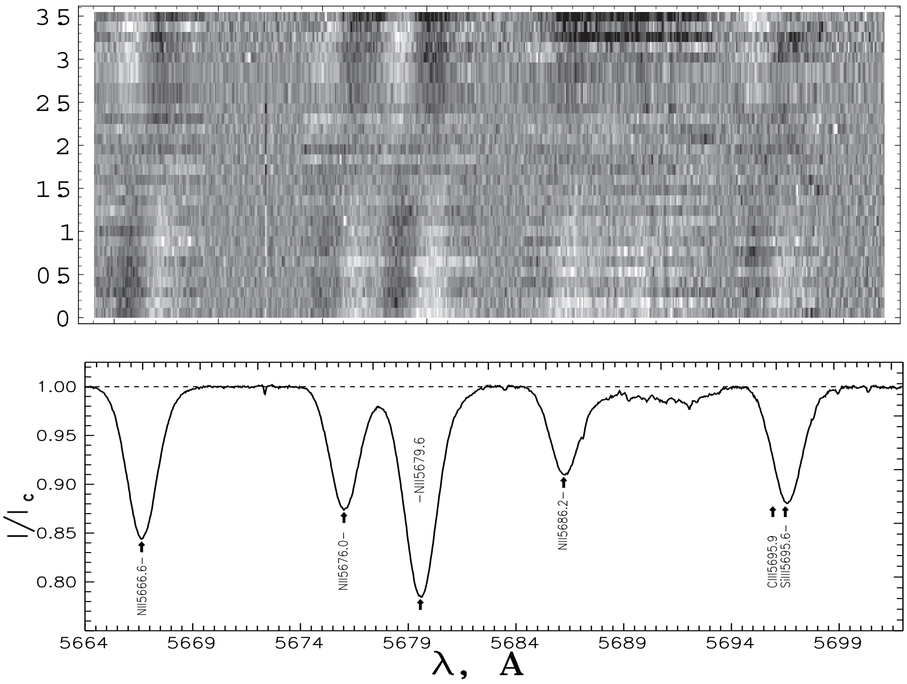

Figure 2: **Top:** density plot of the line profile variations in spectra of ρ Leo in the wavelength region $\lambda\lambda$ 5665-5702 Å. **Bottom:** mean line profiles in the same region averaged over all spectra obtained on Jan. 10/11 2004 .

3.2 Models of cyclical components of the line profile variability

Large time-scale line profile variations are often explained via formation of large-scale structures in the stellar wind. These structures are often connected with corotating interaction regions (CIR, Cranmer and Owocki 1996) resulting from a localized "bright spot" on the stellar surface. These CIRs are thought to produce the cyclical modulation of the P-Cygni absorptions in optical and UV lines (e.g. Kaper et al. 1999, de Jong et al. 2001).

An alternative explanation of the cyclical line profile variations can be obtained in the framework of a "confined corotating wind" model. In this model a star is an oblique magnetic rotator (see, for example, Fig. 15 in Rauw et al. 2001). Such a model has been proposed to explain the *lpv* observed in the spectra of ζPup (Moffat and Michaud 1981) and θ^1 Ori C (Stahl 1996).

4 Magnetic fields of OB stars

4.1 Magnetically confined wind-shock model

Babel and Montmerle (1997)
have developed a magnetically confined wind-shock (MCWS) model. In this model the wind streams from both magnetic hemispheres, collide with each other and produce strong shocks, an extended X-Ray-emitting post-shock region and a thin dense cooling disc in the magnetic equatorial plane. In this model it is possible to explain the stellar disks (Cassinelli et al. 2002) around Be stars (see also Brown et al. 2004). We can also remark that the material in this model may be unstable against falling back (UdDoula and Owocki 2002).

The possibility of generation of magnetic fields on the surface of hot stars by a dynamo mechanism is often supposed (eg., MacGregor and Cassinelli 2003). They found that fields in hot main-sequence stars are generated by a dynamo mechanism at the interface between the radiative core and convective envelope of a star. The generated magnetic tubes could rise to the surface and reach the necessary level for the wind confining.

4.2 Magnetic field of ρ Leo

Observations of ρ Leo with the polarized analyzer and data reduction procedures are descibed in Section 2. The equipment for measuring stellar magnetic fields designed for the spectrograph MSS at the 6 m telescope is described by Chountonov (2004). For example, we plot the part of spectra of ρ Leo obtained with the polarization analyzer in Fig. 3.

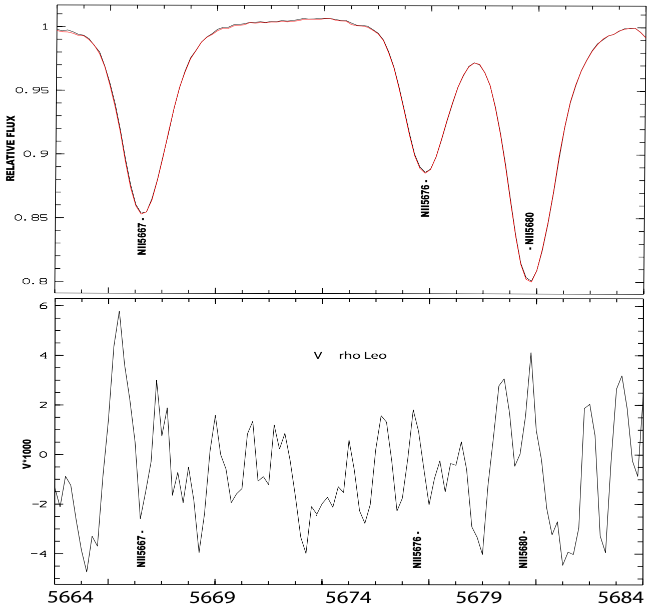

Figure 3: **Top**: left and right polarized components in spectra of ρ Leo in the region $\lambda\lambda\,5664 - 5684$ Å. **Bottom**: profile of the Stokes parameter V in the same spectral region.

For determining the field value we used the cross-correlation method (see, for example, Semenko 2004). Results of our measurements of mean longitudinal magnetic fields $\overline{B}_l$ are given in Table 3.

Table 3: Field measurements of ρ Leo

Date	UT	$\overline{B}_l$, G
2005-1-30	19h 55m 12.00s	$+33 \pm 19$
2005-1-10	0h 43m 11.99s	-93 ± 27
2005-1-12	0h 57m 36.00s	$+31 \pm 24$
2005-1-13	1h 55m 12.00s	-21 ± 14
2005-1-14	0h 0m 0.00s	$+69 \pm 17$

As a first approximation, we can suppose a dipole geometry of the ρ Leo's field. In this case the measured value $\overline{B}_l$ is the line intensity weighted mean over the entire stellar disk (Eversberg 1997):

$$\overline{B}_l = \frac{1}{W_\lambda}\int\limits_0^{2\pi} d\varphi \int\limits_0^{\pi/2} B_l \cos(\theta)\sin(\varphi)d\theta \times \int r_\lambda(\theta,\varphi)d\lambda\,. \tag{1}$$

Here $B_l = B_l(\theta,\varphi)$ is the line of sight component of the magnetic field at the point (θ,φ), where θ

and φ are the coordinates of the point at the stellar disk and $r_\lambda(\theta, \varphi)$ is the residual intensity of the line at this point.

For a tilted dipole magnetic field geometry and a linear law of limb darkening $r_\lambda(\theta, \varphi) \propto 1 - u + u\cos(\theta)$ (u is the parameter of limb darkening for the wavelength considered) the variation of $\overline{B}_l$ with rotational phase ϕ can be obtained by integration of Eq.1. Finally (see, e.g. Preston (1967) for details):

$$\overline{B}_l = B_p \frac{15+u}{20(3-u)}[\cos\beta\cos i + \sin\beta\sin i\cos 2\pi(\phi - \phi_0)]\,, \tag{2}$$

where B_p is the polar magnetic field strength, β is the angle between the magnetic and rotational axes, i is the rotational axis inclination angle and ϕ_0 is the phase of the maximal longitudinal field.

Using the standard least mean square approximation, we fit the obtained values of B_l in the tilted magnetic dipole model. For parameter u we use the standard value $u = 0.350$ for early B stars (Schrijvers 1997). Parameters of the fit for ρ Leo are given in Table 4. The rotational phase for dates of observations were calculated using the possible rotational period $P = 7.267$ d and the value of $T_O = 2453377.611$ (Kholtygin et al. 2006c).

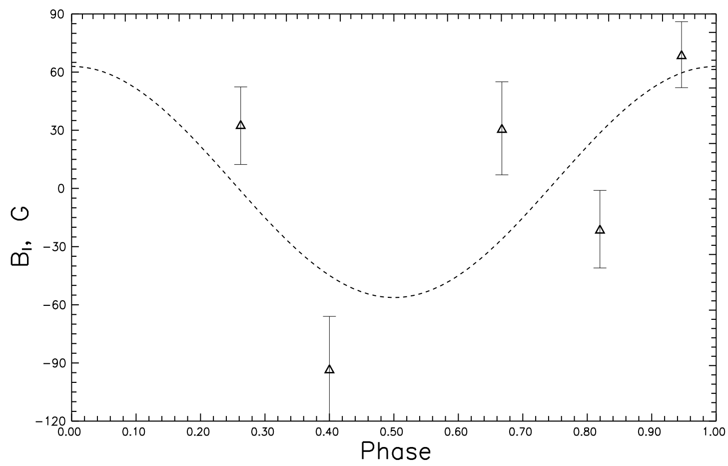

Figure 4: Fit of the longitude components B_l of the ρ Leo magnetic field (triangles) in the model of Preston (1967), the tilted magnetic rotator — dashed line. The rms error of values B_l are also shown.

5 Discussion of results

In Table 4 we compile the results of the recent measurements of the magnetic field for OB stars basing on some recent investigations together with our data for ρ Leo. In the table B_p is the polar field in the case where the tilted dipole model is accessible and the mean field averaged over all measurements in other cases.

We see that the parameters of the possible magnetic field of *ρ Leo* are close to those of O and early B stars. That gives an additional argument in the favor of our supposition about the dipole geometry of the field of *ρ Leo*.

Other arguments go from the detection a weak regular lpv in spectra of *ρ Leo* out of the $V\sin i$ zone (see Kholtygin et al. 2006c for details). Such a type of variability can occur if the matter just near the star (1–2 stellar radii) co-rotates with the stars itself. Connection between pulsations and regular structures in the wind was pointed out by Owocki and Cranmer (1988).

Possibly the most intriguing problem of stellar physics is the *origin of the magnetic field* of the early-type stars. There exist two possibilities. The first is a hypothesis that the field is being

Table 4: Field measurements for OB stars

Star	Spectral Class	Vsini, km/s	P, d	Bp, G	β	i	References
θ^1 Ori C	O6 Ipe	45	15	1110 ± 100	$45^o \pm 17^o$		Donati et al. 2002
HD 191612	08	102	538	-1500 ± 200	45^o	45^o	Donati et al. 2006b
τ Sco	B0.2V	5	41	500			Donati et al. 2006a
β Cru	B0.5III	16		18^{**}			Hubrig et al. 2006b
β CMa	B1 II-III	11		35^{**}			Hubrig et al. 2006b
ρ Leo	B1Ib	95	7.3	240 ± 50	$59^o \pm 30^o$	$85^o \pm ^o$	Present paper
ξ^1 CMa	B1III	20		232^{**}			Hubrig et al. 2006b
κ Sco	B1.5III	97		73^{**}			Hubrig et al. 2006b
ν Eri	B2III	21		33^{**}			Hubrig et al. 2006b
HD 85953	B2III	-		-131 ± 42			Hubrig et al. 2006a
HD 74195	B2III	-		-277 ± 108			Hubrig et al. 2006a
V386 Cen	B2	8		67^{**}			Hubrig et al. 2006b
β Cep	B2IIIevar	20		360 ± 40	$85^o \pm 10^o$	$60^o \pm 10^o$	Henrichs et al. 2003
V335 Vel	B2III	18		103^{**}			Hubrig et al. 2006b
ζ Cas	B2IV	17	5.4	340 ± 90	$80^o \pm 4^o$	$18^o \pm 4^o$	Henrichs et al. 2003
θ Oph	B2IV	16		-39 ± 21			Hubrig et al. 2006b
v 2052 Oph	B2 IV-V	60	3.6	250 ± 190	$35^o \pm 17^o$	$71^o \pm 10^o$	Henrichs et al. 2003
HR 2718	B2IV-V	95		873 ± 66			Hubrig et. al. 2006
V539 Ara	B2V	-		-39 ± 21			Hubrig et al. 2006b
o Vel	B3IV	9		200^{**}			Hubrig et al. 2006b
HY Vel	B3IV	13		146^{**}			Hubrig et al. 2006b
V514 Car	B3IV	41		37^{**}			Hubrig et al. 2006b
ζ Cir	B3V	264		$-106 \pm 46^*$			Hubrig et al. 2006b
16 Peg	B3V	104		133^{**}			Hubrig et al. 2006b
ω Ori	B3 IIIe	172	1.3	530 ± 200	$50^o \pm 25^o$	$42^o \pm 7^o$	Henrichs et al. 2003

Comments: * – single measurement of longitudal magnetic field, ** – average longitudal magnetic field over all measurements

generated by a contemporary dynamo mechanism (MacGregor and Cassinelli 2003). The second postulates that the field is *fossil*. It means, that the field is a dynamically stable relic of the field in the molecular cloud where the star formed, or of a field built by a dynamo acting in a pre-main sequence phase of the star (Mestel 2003).

In the case of *dynamo* action there have to be a correlation between the field strengths and the rotation velocity. However, we have inspected the data presented in Table 4 and have not found any correlation of such a kind (see Fig. 5).

Moreover, Braithwaite and Nordlund 2006 have recently resolved the most serious problem of the *fossil* theory, the stability of the field during stellar evolution. It was found that stable magnetic field configurations exist under the conditions in the radiative interior of a star. Such configurations have roughly equal poloidal and toroidal field strengths. We can conclude that the *fossil* nature of the OBA stellar field seems to be more substantial.

6 Conclusion

We report the results of a study of fast *lpv* in spectra of the bright B1 supergiant ρ Leo and search for magnetic field. Regular long time-scale components of *lpv* in spectra of the star have been detected.

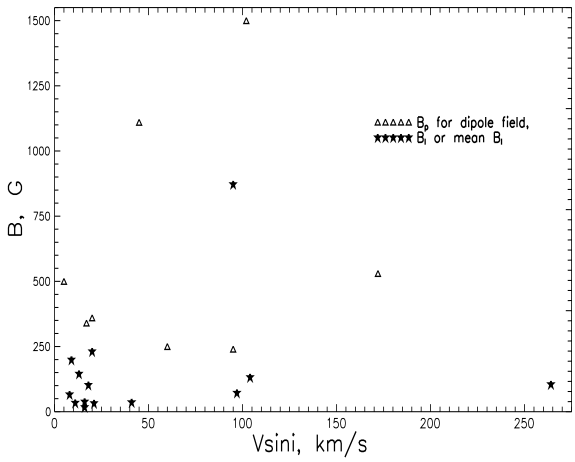

Figure 5: The polar magnetic field values B_p (triangles) and the mean line of sight component of the magnetic field B_l (asterisks) vs. projectional rotational velocities $Vsini$.

The formation of such components of *lpv* can be explained in the framework of the MCWS model by Babel and Montmerle (1997).

Acknowledgements. The authors are grateful for the support provided by RFBR grants 5-02-16995 and 06-02-17096

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