V2494 Cyg: A unique FU Ori type object in the Cygnus OB7 complex

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ABSTRACT

A photometric and spectral study of the variable star V2494 Cyg in the L 1003 dark cloud is presented. The brightness of the star, formerly known as HH 381 IRS, increased by 2.5 mag in R (probably in the 1980s) and since then has remained nearly constant. Since the brightness increase, V2494 Cyg has illuminated a bipolar cometary nebula. The stellar spectrum has several features typical of the FU Ori type, plus it exhibits very strong Hα and forbidden emission lines with high-velocity components. These emission lines originate in the HH jet near the star. The kinematic age of the jet is consistent with it forming at the time of the outburst leading to the luminosity increase. V2494 Cyg also produces a rather extended outflow; it is the first known FUor with both an observed outburst and a parsec-sized HH flow. The nebula, illuminated by V2494 Cyg, possesses similar morphological and spectral characteristics to Hubble's Variable Nebula (R Monocerotis/NGC 2261).

Key words: stars: pre-main-sequence – stars: individual: V2494 Cyg – ISM: jets and outflows

1 INTRODUCTION

Objects classified as FU Ori type (FUors), though very rare, provide clues to the understanding of star formation processes and the evolution of pre-main sequence (PMS) objects. Their main features are well-known (Herbig 1977; Hartmann & Kenyon 1996). Their key attribute is a sudden significant rise in brightness (up to 5 – 6 magnitudes in V) in a relatively short period (0.5 – 10 years), after which the object usually remains bright with little variability for tens of years. Other typical qualities include:

a close association with a compact reflection nebulae;
a large excess of radiation at UV and IR wavelengths,

a spectral type after the eruption similar to F–G supergiants, with
earlier type spectra in the UV, and later type in the IR,
deep CO absorption features,
the presence of prominent P Cyg profiles in Hα and Na D lines, indicating mass loss at up to 1000 km s^{-1} velocity, and
the presence of Li I spectral lines, indicating the youth of the star.

Only about twenty such objects are known at present (Reipurth & Aspin 2010), half of them being classified as "classical" FUors (i.e. those where the outburst has been observed), and the other half, classified as FUor-like, are represented by stars which have similar spectral characteristics but where no outbursts have been detected (i.e. it is assumed that they were discovered after the outburst).

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According to the generally accepted model of the FUor phenomenon, the sudden brightening is probably due to a significant increase in accretion (up to 10^{-4} M$_{\odot}$) from the circumstellar matter onto the T Tau star (Hartmann & Kenyon 1996). Disturbances to the accreting disk creating such an increase may be caused by thermal instabilities (Bell & Lin 1994), or may be due to a close companion (Bonnell & Bastien 1992; Reipurth & Aspin 2004) or giant planet in the disk (Lodato & Clarke 2004). A comprehensive review of these models can be found in the book of Hartmann (2009). However, notwithstanding the successful explanation of some features of FUors by this approach, many questions still remain open. Herbig, Petrov & Duemmler (2003), for example, suggest that a number of the observational aspects may be better explained if the star itself, rather than an accretion disk, is responsible for the FUor flare-up. For example, such an increase in brightness can occur for stars with anomalous high rotation velocities (Larson 1980). One should also keep in mind that there exist a number of PMS stars which display certain FU Ori features (e.g. V1331 Cyg, V1647 Ori) and are considered by some authors to be pre-FUors or post-FUors. Besides, yet another and also not numerous class of PMS variables, EXors, can be related to the FU Ori phenomenon (see Reipurth & Aspin 2010, and references therein). Thus, in future, when the volume of observational data increases, the criteria for defining the object as FUor may be expanded. In this paper, however, we will keep close to the genuine FU Ori picture.

No FUor has so far had more than one outburst detected. However, from statistical considerations, it is usually accepted that FUors should exhibit recurring eruptions with a timescale of order 10^4 years (Herbig 1977; Hartmann & Kenyon 1996; Scholz, Froebrich & Wood 2013). In this connection it is tempting to make a direct connection between probably-repetitive FU Ori outbursts and extended Herbig-Haro (HH) outflows with multiple working surfaces (implying the periodic release of of matter from young stellar sources) (Reipurth 1989; Reipurth & Aspin 1997; Reipurth & Bally 2001; Herbig et al. 2003; Movsessian et al. 2006).

Another crucial but still open question concerns the fraction of typical low-mass stars which undergo the FU Ori phenomenon in their early evolution. To date, only classical T Tauri stars have been directly found to undergo FU Or outbursts. For a long time the only object with a known pre-outburst spectrum remained the V1057 Cyg star; the recent discovery of a FU Ori type eruption in LkHα 188-G4 (Miller et al. 2011) raises the number of such objects to two. Both stars prior to eruption were classical T Tau stars.

However, the timescale between outbursts of order 10,000 years makes these events extremely rare. If all accreting young stars undergo the outbursts, then it is probable that the first discoveries will be within the largest and easiest observed class of accreting object. If this timescale applies to other types of YSO, then similar outbursts may be revealed in them once similar extended surveys are performed.

The situation, doubtless, will be elucidated in the future, when we will have pre-outburst spectral energy distributions for newly discovered FUors, which would then probably occur in the large number of the presently performed infrared surveys such as 2MASS, IRAS, Spitzer, AKARI and WISE. The work of Scholz et al (2013) should be mentioned as an example of ongoing surveys for FU Ori objects.

We present here the results of new observations in the optical range of the probable FU Ori-like object V2494 Cyg, also known as IRAS 20568+5217 and HH 381 IRS (Reipurth & Aspin 1997). This object is associated with a bright cometary nebula and several HH objects (Devine, Reipurth & Bally 1997). It is located in the dark cloud L 1003, belonging to the Cyg OB7 star-forming complex (Movsessian et al. 2003) where another FU Ori type object, V2495 Cyg, has been identified (Movsessian et al. 2006; Magakian et al. 2010). V2494 Cyg possesses a jet and a large bipolar outflow traced by HH objects and Molecular Hydrogen emission-line Objects (MHOs). These include HH 382 and HH 966 as well as MHO 900, 901, 902 and 904 (Magakian et al. 2010; Khanzadyan et al. 2012).

The similarity of the infrared spectrum of V2494 Cyg to other FUors has already been noted by Reipurth & Aspin (1997). Further studies in the infrared range have confirmed this conclusion (Aspin et al. 2009). At the same time its recent brightening in the optical range was also revealed (Magakian et al. 2007).

The distance to the L 1003 cloud was estimated only roughly. Hereafter we will assume the value 800 pc for V2494 Cyg and for the entire Cyg OB7 complex (Dobashi, Bernard & Fukui 1996), consistent with all our previous works (Aspin et al. 2009; Magakian et al. 2010; Aspin et al. 2011; Khanzadyan et al. 2012).

In Sect. 2 we describe the observational methods and data reduction. In Sect. 3 results of the photometry and the spectroscopy are presented. In Sect. 4 we discuss separately the central star and outflow and summarize our conclusions.

2   OBSERVATIONS AND DATA REDUCTION

Our observations of V2494 Cyg include imaging and photometry as well as spectroscopy in various modes. The observing logs are summarized in Tables 1 and 2. We first describe these observations in more detail.

2.1   Imaging

Image archives as well as new observations were used for photometry of the star and for analysis of the morphology of the associated cometary nebula. Archival data were from the DSS-1, Quick-V, DSS-2 and SuperCOSMOS (SSS) digital sky atlases, as well as images from the IPHAS survey, obtained on 2003 November 10-14 (Drew et al. 2005). In addition, a number of photographic plates from the Tautenburg plate archive, obtained in 1975-1985, were checked for the presence of the object (Helmut Meusinger, private communication).

New imaging data, to check the recent variability of the object, were obtained on 2006 September 22-24 in R and I using the Subaru Prime Focus Camera (Suprime-Cam, Miyazaki et al. 2002) mounted at the prime focus of the 8.2-m Subaru Telescope atop Mauna Kea, Hawaii (described in the previous work: Magakian et al. 2010); two direct images, obtained in 2008 with a CCD-camera on the ZTSh 2.6-m telescope of the Crimean Observatory; plus a number of images, obtained with exposures of 600 sec

with the ByuFOSC-2 (Movsessian et al. 2000) and SCOR-PIO (Afanasiev & Moiseev 2005) prime focus cameras on the 2.6-m telescope ZTA of Byurakan Observatory in 2008-2010.

The Byurakan and Crimean images were reduced with standard procedures for aperture photometry. Magnitudes were converted to the Cousins photometric system. For photometric calibration, standard stars from the NGC 7790 cluster (Landolt 1992) were taken. In addition, we used three non-variable stars in the L 1003 cloud as secondary standards, for which we determined R_C and I_C magnitudes. To compare the new and archive data and to avoid systematic errors as far as possible, we re-measured all sky survey images, calibrating them by nearby stars, magnitudes of which were taken from the GSC 2.3.2 catalogue which could be considered as the best photometric source for these purposes (Mickaelian, Sarkissian & Sinamyan 2012).

The observation dates of all images used in this paper are listed in Table 1 along with the photometric results.

2.2   Slit spectroscopy

The optical spectrum of the star V2494 Cyg and of the its associated nebula was observed in 2007 January 10 with the 6-m telescope of SAO (Russia) using the SCORPIO multi-mode focal reducer (Afanasiev & Moiseev 2005), mounted at the prime focus of the telescope. In the long-slit mode the instrument was equipped with the VPH1800R grating, which provides a ∼2.5 Å resolution and a spectral range of 6100-7100 Å. A 2048 × 2048 EEV 42-40 CCD was used for the detector; after binning by 1 × 2 the scale was 0.36 arcsec per pixel along the slit. Total exposure time was 1200 sec and seeing was 1.6 arcsec. The position angle of the slit during the observations was 343°; this direction is aligned with the jet and the axis of the reflection nebula.

Data reduction was performed with a package of procedures developed in IDL by A. Moiseev at SAO. This package includes standard operations, such as flat-fielding, wavelength and flux calibration. Further analysis was done with the ESO MIDAS image processing system.

We also made an attempt to obtain a long-slit spectrum of the knot A in HH 382 group, using the SCORPIO focal reducer on the 2.6-m telescope in Byurakan. The measurable spectrum of HH 382A was registered in the red range ($\lambda\lambda 5900-6900$) on 2008 June 13, with a total exposure time of 3600 sec and 0.5 Å/pix dispersion.

2.3   Imaging Spectroscopy

Imaging spectroscopy observations were obtained using the SCORPIO prime focus multi-mode device equipped with a scanning Fabry-Perot etalon and 2048 × 2048 EEV 42-40 CCD, mounted on the 6-m SAO telescope. The field around V2494 Cyg, which includes the jet and nearby HH knots, was observed in the $H\alpha$ line on the 28th of June 2008. Observations were performed with 4 × 4 pixel binning to reduce the readout time and enhance the S/N ratio; 512 × 512 pixel images were obtained for each spectral channel. The field of view was 6.1 × 6.1 arcmin with a scale of 0.71 arcsec per pixel. An interference filter with FWHM = 15 Å centered on the $H\alpha$ line was used for pre-monochromatization. For our

observations we used a Queensgate ET-50 etalon operating in the 501st order of interference at the $H\alpha$ wavelength, and providing an instrumental profile of FWHM ≈ 0.8 Å (or ∼ 36 km s^{-1}) for a range of $\Delta\lambda$=13.2Å (or ∼ 605 km s^{-1}), free from order overlapping. The number of spectral channels was 36 and the size of a single channel was $\Delta\lambda \approx 0.37$ Å (∼ 17 km s^{-1}).

We reduced our Fabry-Perot observations using software developed at SAO (Moiseev & Egorov 2008). After primary data reduction, subtraction of night sky lines and wavelength calibration, the observational material represents data cubes where each point in the 512 × 512 pixel field contains a 36 channel spectrum. For data analysis we used the ADHOCw software, developed by the Interferometry Group of Marseille Observatory[1] (see Garrido et al. 2002 for an example of Fabry-Perot data reduction).

3   RESULTS

3.1   The nebula imaging

As already mentioned above, this spectacular bipolar nebula is missing in common catalogs. It was described for the first time in the work of Devine et al. (1997). We have reviewed its photometric history and found that the object became significantly brighter in the period between the DSS-1 and DSS-2 surveys, i.e. from 1952 to 1989. In 1952 the central star, which is associated with the IRAS 20568+5217 source, is detectable only on the DSS-1 red image, near the plate limit. In 1983, in the Quick-V sky survey, the star is definitely brighter (especially when one considers the different bandwidths of both surveys and the very red colour of the star) and traces of the nebula can be seen. On the DSS-2 R (1990) and I (1991) charts the nebula is well developed and is also now visible in the bluer wavebands (DSS-2 B, 1989). The discovery image, obtained in 1995-1996 (Devine et al. 1997), shows the nebula with essentially the same appearance as in our new images. Thus, the increase of the brightness started after 1952 and, probably, not long before 1983.

For the last 15-20 years the star seems to have reached the light curve plateau. Its photometric history is described in the next section. We show images of the object taken at various epochs in Fig. 1.

The morphology of the nebula, associated with V2494 Cyg, differs in the optical and near-IR in much the same way as for the nearby Braid Nebula (Movsessian et al. 2003, 2006). To make this comparison we used the optical R_C images obtained in 2006 with Suprime-Cam on the Subaru telescope and the near-IR images obtained in the K-band with WFCAM on UKIRT. These data are described in detail in the papers of Magakian et al. (2010) and Khanzadyan et al. (2012). For clarity we present both images superposed in Fig. 2 (left panel).

To begin with, the orientation of the axis of the nebula is not easy to define. At optical wavelengths the northern cone is more extended but has a lower surface brightness and, as a whole, is aligned almost north-south. However, its apex appears significantly detached and shifted from the
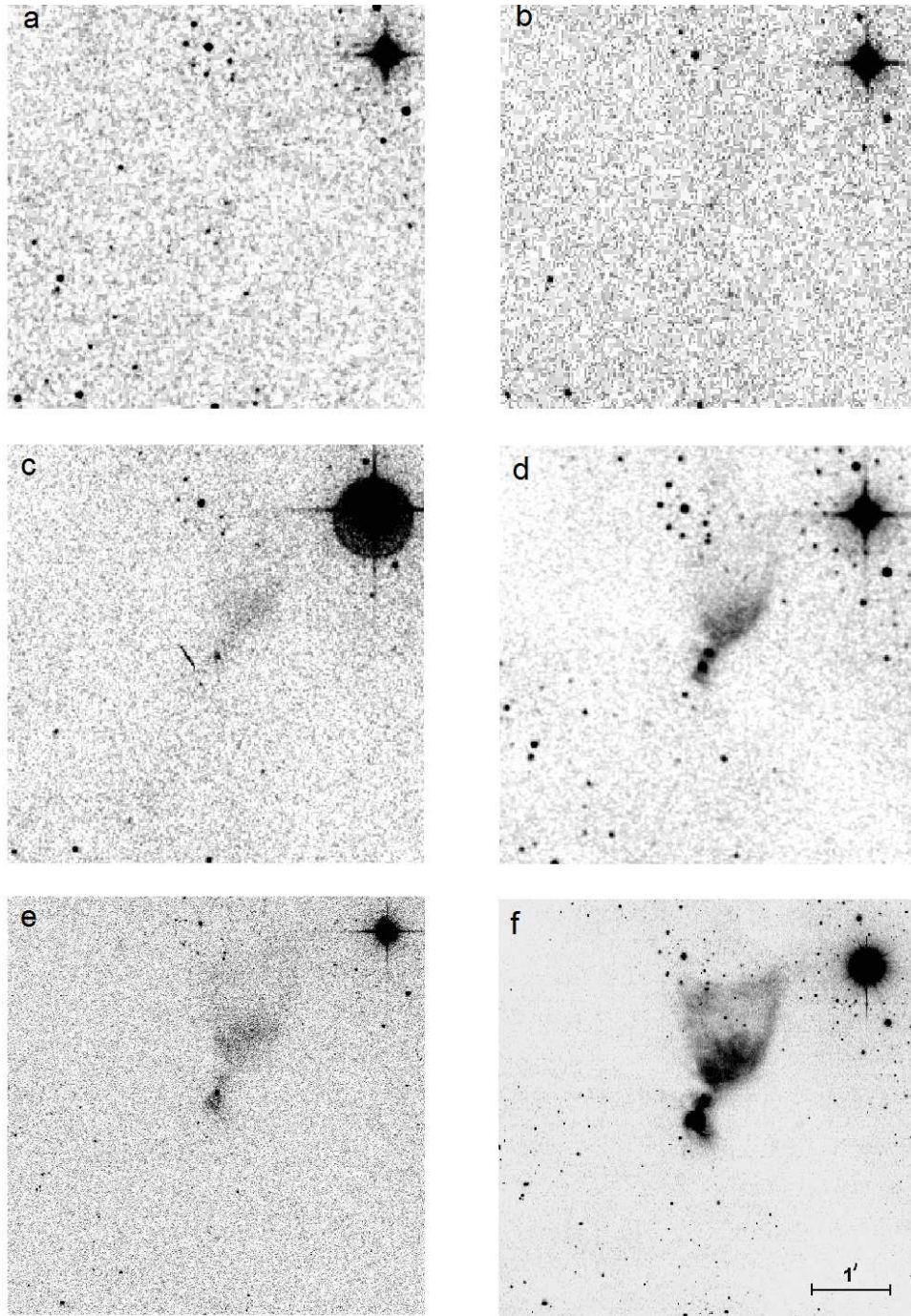
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[1] http://www.oamp.fr/adhoc/adhocw.htm

Figure 1. The appearance of the V2494 Cyg and its associated nebula in various epochs. Panels: a) - POSS-1 R, 1952 (SSS survey); b) - Quick V, 1983; c) DSS-2 B, 1989; d) - DSS-2 R, 1991; e) IPHAS survey, R, 2003; f) - Subaru R, 2006. North is up, east is left. The object is located in the centre of the panels. The streak to the east from the star on the panel c) is an artifact on DSS-2. Note the bright nebulous knot in NW direction from the star on the panel d). The size of the each panel is about 5.3 × 5.3 arcmin.

source star because of a dark lane that cuts across it, producing between them another bright knot. The southern lobe appears more inclined to the south-east; however, another narrow dark lane near the central source with a position angle of 75° gives definitely greater deviation from the N-S direction. These features must be the result of foreground extinction variations, because, as is clearly seen in Fig. 2a, in the near-IR the nebula is symmetric and essentially oriented

north-south. Note the total lack of background stars in the optical range image to the east and west of the reflection nebula (Fig. 1f), which shows that our object is located in the centre of the elongated dark cloudlet. Note also that in the optical range the western side of the northern cone has parabolic shape while its eastern side is nearly linear, being abruptly cut by the extinction.

In the K-band image the northern cone is fainter, but

its walls are more clearly defined, especially the eastern side, which seems to be fully absorbed in the optical image. The opening angle of the northern lobe appears larger in the near-IR. Actually, the near-IR image seems brightest just in the places where the extinction in optical range is greatest. The southern lobe appears significantly lower inclined to the east and has a much higher surface brightness compared to the northern lobe. Thus, we can assume that the real symmetry axis of the nebula is oriented much closer to north-south than implied by the optical images. This is in full accordance with the direction of the parsec-size bipolar outflow from the central star (Magakian et al. 2010).

The spectacular biconic appearance of the nebula points to its small inclination angle to the plane of sky. However, its morphology suggests that the northern cone should be inclined toward us; this conclusion is corroborated by the spectral data (see below).

A comparison of the DSS-2 and our recent Subaru images does not show major morphological differences in the shape and brightness of the nebula.

3.2 Photometry of the central star

In order to attain a better understanding of the photometric history of V2494 Cyg we collected brightness estimates from observations taken at various epochs.

The first available image of the central star that we found was in the POSS-1 survey red plate, obtained on 17 September 1952. The source magnitude in the USNO-B1.0 catalog (Monet et al. 2003) (where the central star of the nebula is listed as object 1424-0432369) is given as R1=18.57. Our measurements give nearly the same value. However, on checking the image of V2494 Cyg in the SSS survey, which was performed with better resolution than DSS-1, one can clearly see that even in this epoch the object is extended and not purely star-like. The brightness of the central star may therefore be overestimated. In any case the star definitely became brighter in the 80-ies: from a Quick-V survey plate (data obtained on 8 July, 1983) we measured the brightness to be 17.52 mag in V.

The blue plates from the Tautenburg collection, which span a period from September 1975 to July 1985, show that the star is always below the plate detection limit (which for various plates is estimated to be in the range 17.20 to 20.58 mag in B).

On DSS-2 plates the USNO-B1.0 magnitudes of the 1424-0432369 star are as follows: B2=19.90; R2=13.74; IN=12.13. The errors on these values are estimated to be about 0.25 magnitude. However, after further analysis of the DSS-2 images and neighboring objects in the USNO-B1.0 catalogue, we came to conclusion that the measurements in R2 and IN can be erroneous, because V2494 Cyg was recognised in the catalog as an extended object, which led to a significant over-estimate of its brightness. Indeed, on the DSS-2 R and I images all neighboring stars with the same peak counts are cataloged in USNO-B1.0 with significantly higher values of R2 and IN magnitudes, i.e. as much fainter objects than V2494 Cyg. Because of these factors we re-estimated the magnitudes of the central star of the nebula on all images taken from the DSS and SSS digital surveys, using the point-spread-functions (PSF) of field stars. These results are included in the Table 1.

Table 1. The photometry of V2494 Cyg (HH 381 IRS)

Image, Epoch	B	V	R	I	R−I
DSS-1 17.09.1952			18.7		
Quick-V 08.07.1983		17.5			
DSS-2 24.08.1989	20.8				
DSS-2 29.08.1989	20.3				
DSS-2 24.08.1990			16.5		
DSS-2 06.07.1991				14.9	
DSS-2 04.09.1991			16.3		
DSS-2 03.07.1993				14.6	
IPHAS 14.11.2003			16.85	15.06	1.79
SUBARU 25/26.09.2006			16.52	14.91	1.61
ZTSh 22.05.2008			16.29	14.51	1.78
ZTSh 16.06.2008			16.36	14.56	1.80
ZTA 25.06.2008			16.29	14.56	1.73
ZTA 06.10.2008				14.49	
ZTA 24.06.2009			16.32	14.71	1.61
ZTA 28.06.2009			16.09	14.47	1.62
ZTA 06.11.2009			16.15	14.49	1.66
ZTA 06.08.2010			16.34	14.76	1.58
ZTA 02.11.2010			16.39	14.57	1.82

Photometric data for DSS-1 are taken from USNO-B1.0 catalog; all other values are our own estimates (see text).

To obtain recent photometric values as well as to look for possible brightness variations we used several sets of images of the object obtained since 2003. These include the IPHAS survey images (Drew et al. 2005), our 2006 Subaru images, and the observations from the 2.6-m telescopes in Byurakan and Crimea. All these measurements also are included in Table 1. As can be seen from Table 1, for more than twenty years the brightness of the star has fluctuated by less than 0.3^m amplitude from the mean value; its colour also remains nearly constant. There are no signs of fading.

In summary, we conclude that the increase in brightness of the V2494 Cyg very probably started in the early 1980s; in the period between 1990 and 2000 the star already reached its maximum visible brightness and since then has remained at this luminosity. The absence of the star on the Tautenburg plates (even though in B it should be very faint) gives some support to this conclusion in the sense that there were no major outbursts before 1983. The amplitude of 2.5 mag in R is probably a lower limit, since even at the time of the POSS-1 survey observations the star was slightly nebulous and therefore extended. In fact, on the base of our preliminary reports the object is already recognized as a variable star and numbered as V2494 Cyg (Kazarovets, Reipurth & Samus 2011). We suggest that in future only this name be used for the central source within the nebula. Note in particular that the star actually is not associated with HH 381 (see below), so the name HH 381-IRS should certainly be avoided. The nebula in turn can be referred to as "the V2494 Cyg nebula"; on the other hand, "the IRAS 20568+5217 nebula" name also could be kept for the identification purposes (it was named as such when first detected by Devine et al. 1997.).
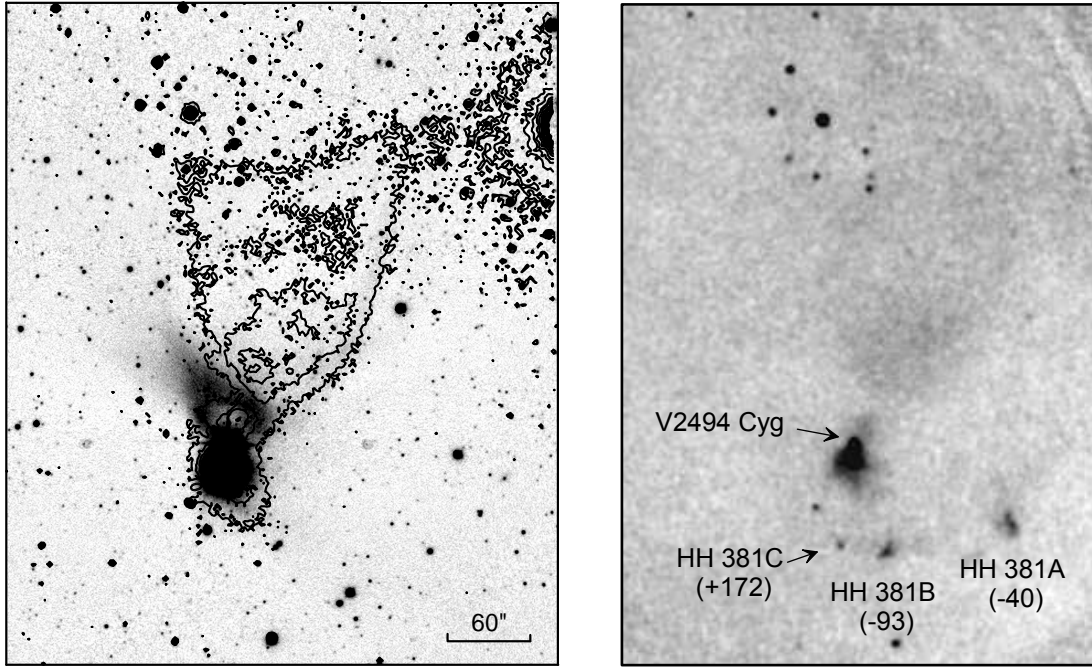
Figure 2. Left panel: the superposition of the V2494 Cyg nebula images in K (gray scale) and in R$_C$ (isolines). Both images were obtained in 2006 (see sec. 2.1 and 3.1 for the further details). Right panel: the monochromatic Hα image of the same field, restored from the FP data. The HH 381 knots A, B and C and their radial velocities in km sec^{-1} are marked (see sec. 3.5). Both panels are in the same scale.

Table 2. The log of spectral observations

Date	Object	Telescope, system
10.01.2007	V2494 Cyg (star+nebula)	6-m, SAO, long-slit
13.06.2008	HH 382A	2.6-m, Byurakan, long-slit
29.06.2008	V2494 Cyg field	6-m, SAO, scanning FP

3.3 Slit spectroscopy of the central star, nebula and bipolar jet

In the slit spectrogram, described above, the spectra of the central star and of the neighboring parts of nebula were registered.

The spectrum of V2494 Cyg, extracted by using the stellar PSF, is shown in Fig. 3. We see the reddened stellar continuum with prominent emission lines (Hα, [OI], [NII] and [SII]) superimposed. Such strong emission lines, unusual for FUors, almost certainly belong to the collimated, ionized jet that is visible in published direct images (Magakian et al. 2010).

The only strong stellar absorption, which is evident in Fig. 3, is the strong Ba II blend near $\lambda6495$. This feature is typical of G supergiants and thus distinctive for FU Ori type spectra (Reipurth et al. 2002). As can be seen from the Fig.2 and Fig.4 of that paper, there are no other conspicuous absorption features, which one might expect to see in the observed wavelength range with our spectral resolution. As for the P Cygni absorption component in the Hα line, which are usually prominent in the spectra of FU Ori type stars, it is very probably masked by the rather strong emission line of the jet (see, however, sec 3.4).
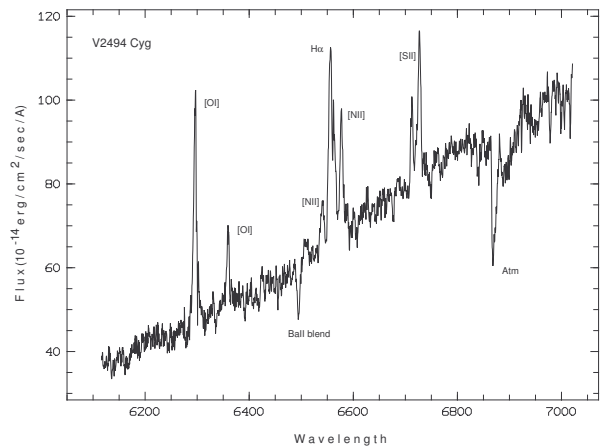

Figure 3. The optical spectrum of the V2494 Cyg in red range, obtained with 6-m telescope. All major features are identified.

The observed emission lines, especially Hα, have complex profiles and are extended along the slit. To investigate the emission spectrum in more detail we have subtracted the continuum from our reduced spectral image, separately fitting and subtracting the stellar spectrum row by row. The result is shown in Fig. 4. The slit orientation is shown in Fig. 5. In Fig. 4 we see that the intensity maxima of all main emission lines are shifted to the north with respect to the stellar continuum. This fully confirms that the emission originates in the ionized jet that extends to the north from the central star (Magakian et al. 2010). In Fig. 4 the jet emission features are labelled with the number 2; signs of the
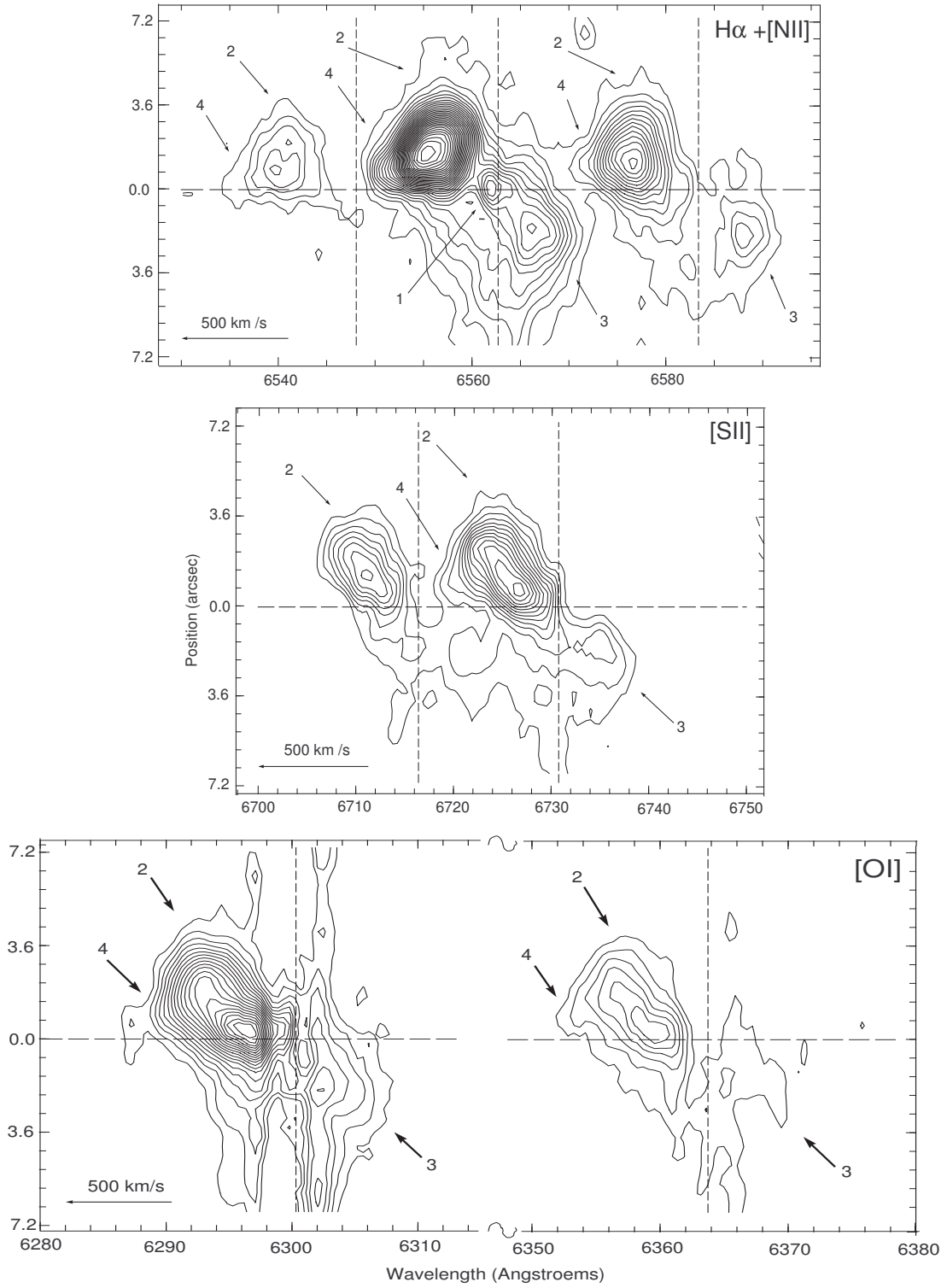
Figure 4. Continuum-subtracted long-slit spectrum of the V2494 Cyg star and its vicinities, showing the emission lines of Hα and [NII] (upper panel), [SII] (middle panel) and [OI] (lower panel; vertical artifacts are produced in the process of the bright night sky lines subtraction). Horizontal dashed lines in each panel correspond to the stellar position, and the vertical ones mark the laboratory wavelengths. The slit orientation is indicated in Fig. 5 (right panel). Several discernible components in Hα and other emission lines are denoted by numbers: 1 – probable stellar emission; 2 – the jet emission; 3 – the counter jet emission; 4 – a component with very high negative velocity (see text for their discussion and radial velocities).

counter jet extending to the south are also evident in the data, and are labelled 3 in Fig. 4.

As is also evident in Fig. 4, all emission lines demonstrate complicated spectral and spatial structure. The general trend of a rapid increase in radial velocity (all radial velocities in this paper are heliocentric) with distance from the source (a possible indication of acceleration) is clearly seen in the [SII] and [OI] profiles. The peak velocities in these lines increase from -170 and -197 km s^{-1} near the star to -305 and -348 km s^{-1} at a distance of 2.5 arcsec. In comparison, the [NII] profiles in Fig. 4 are not inclined, though they do exhibit high negative velocities: the [NII] radial velocity measures -313 km s^{-1} at the star position and remains at values of about -320 km s^{-1} along the observed length of the jet. We also note that all of the forbidden line profiles are wide, with Full Width Half Maximum (FWHM) widths of about 250 km s^{-1} (in [SII] FWHM $\sim$ 340 km s^{-1}). The profiles also consist of at least two components separated by about 80 - 100 km s^{-1}. However, our spectral resolution is not sufficient for a reliable multi-component fitting of these profiles.

As was mentioned above, the structure and behavior of the Hα emission profile is the most complicated of all lines observed. The same spatially extended jet component with a near-constant velocity (peak velocity measures -320 km s^{-1} at the star position and -290 km s^{-1} near the observed end of the jet; a similar velocity is observed here in [NII]) is evident in Fig. 4, in addition to a high-velocity component very close to (but not coinciding with) the driving source. This component is labelled 4 in Fig. 4 and can be traced from 0.4 to 1.1 arcsec along the northern flow lobe. We estimate its mean velocity to be -510 km s^{-1}, while its blue wing reaches -645 km s^{-1}. Careful inspection of our data shows that this component can also be seen in forbidden lines, with a mean velocity of about -430 km s^{-1} (in good agreement with the Hα results). The existence of this high-velocity component in $\lambda 6730$ emission combined with its absence in $\lambda 6717$ [SII] emission indicates a high density for the emitting medium. We are inclined to consider this feature as a separate component unrelated to the very broad, single-peaked Hα because it is not symmetric – neither spectrally (it has the appearance of a rather extended emission wing from the blue side of a strong and more sharp core) nor spatially (the brightest Hα emission is offset by about 2 arcsec to the north from the broadest part of the profile).

Finally, we label with number 1 in Fig. 4 a discrete low-velocity peak seen in Hα that is centred at about -20 km s^{-1}. This component is spatially coincident with the maximum of the stellar continuum and is not extended along the slit length (i.e. in a north-south direction). The FWHM of this feature is about 140 - 160 km s^{-1}. With respect to the local standard of rest (LSR), this component is blue-shifted by less than -12 km s^{-1}. To compare, the systemic LSR velocity of the whole cloud is -3.4 km s^{-1} (Moriarty-Schieven et al., in preparation). We therefore identify this component with the star itself. Weak, low-velocity Hα emission lines are typical of FU Ori objects (e.g. Herbig et al. 2003). These are probably too narrow to be associated with accretion (see for example the much wider permitted HI lines observed towards T Tau stars: Folha & Emerson 2000); instead, this emission feature is probably of chromospheric origin. Moreover, the absence of this feature in the observed forbidden line profiles corroborates the conclusion that all strong forbidden emission lines (which are typically absent or very weak in the spectra of classical FUors) belong only to an associated outflow.

The counter jet associated with V2494 Cyg is much fainter in our data, though is nonetheless detected. Emission from the counter jet can be traced 4.3 arcsec to the south of the stellar source continuum. Because of the faintness and complexity of the emission (especially in [SII]), radial velocities are not so easy to measure. Even so, by averaging all lines, we estimate a typical counter jet velocity of $+163 \pm 39$ km s^{-1}. A velocity gradient similar to that seen in the northern lobe cannot be unequivocally identified, although hints of it can be seen in the [SII] and [OI] profiles.

The electron density in the northern jet lobe, estimated from the [SII] line ratio, is about 7000 cm^{-3}; in the southern counter jet a density of around 5000 cm^{-3} is measured. Within the high velocity component densities of more than 10000-11000 cm^{-3} are estimated.

3.4   Scattered light spectroscopy

As was noted earlier, we were not able to detect any signs of Hα absorption in the stellar spectrum, which is probably masked by very strong and broad jet emission. However, during our analysis of the reflected spectrum of the nebula, we quite unexpectedly found that at a distance of about 25 - 50 arcsec to the north of the star the nebula spectrum possesses a strong, broad, and blueshifted Hα absorption feature (Fig. 5). This feature is centred at a velocity of -94 km s^{-1} and exhibits a blue wing that extends up to -700 km s^{-1}. Such a profile is typical of FU Ori objects. As is shown in Fig. 5, this absorption feature is observed toward the northern lobe of the conical reflection nebula while, closer to the source, it is virtually absent. In Fig. 5 we show, for example, a spectrum extracted from the bright knot located at a distance of 6.5 - 15 arcsec from the star (this knot is closer to the central star though is nevertheless far beyond the emission jet).

With this discovery V2494 Cyg and its nebula become one more example of a source exhibiting the rare phenomenon known as "spectral asymmetry". This was first reported in observations of the R Mon + NGC 2261 system (Greenstein 1948a,b; Stockton, Chesley & Chesley 1975; Greenstein et al. 1976). This asymmetry was successfully explained only in the work of Jones & Herbig (1982). We will discuss this unusual feature in more detail below. In the meantime, the detection of the wide P Cyg type absorption feature again confirms the FU Ori nature of V2494 Cyg.

3.5   Spectroscopy of HH knots

As was described above, V2494 Cyg is also referred to as HH 381 IRS because it was believed to be the driving source of nearby HH 381 group of HH objects (Devine, Reipurth & Bally 1997). However, the relationship of the knots that comprise HH 381 to each other and to V2494 Cyg itself was not obvious until the our recent observations.

In the Fig. 2 (right panel) we show the monochromatic Hα image of the field around V2494 Cyg, which is reconstructed from the our FP data. This should be compared
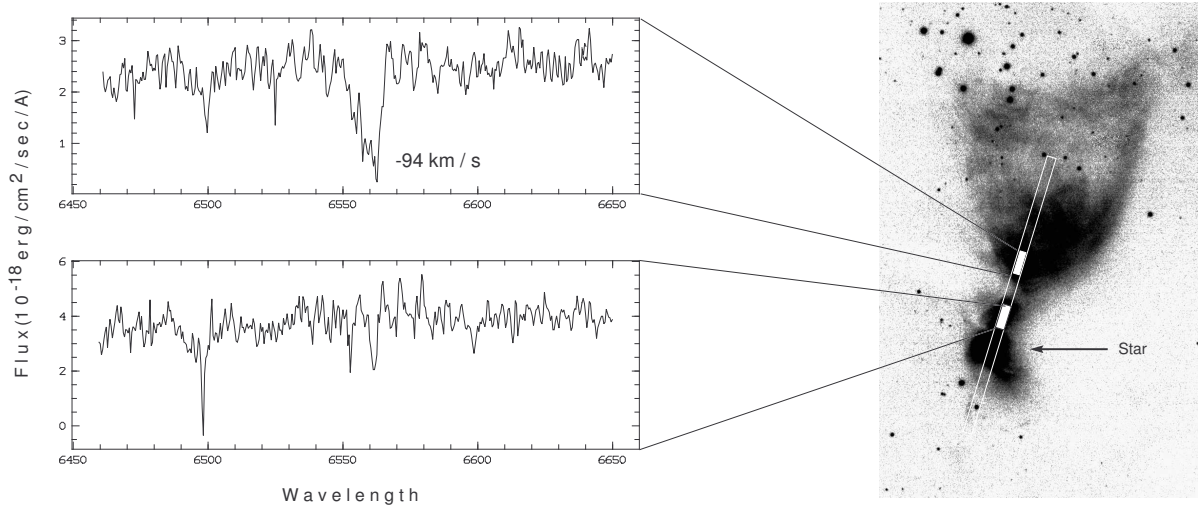
Figure 5. The Hα line profile as seen in the reflection in the distance about 10-15 arcsec (lower panel) and 35-40 arcsec (upper panel) from the star. To increase the S/N ratio several rows of the nebular spectrum are averaged. Note that the blue wing of the asymmetric absorption in the upper panel reaches about -700 km s^{-1} in radial velocity.

with the Fig.4 in Magakian et al. (2010) paper. Our data confirm the emission nature of the HH 381 knots A, B and C and do not show any other nebulous emission objects close to V2494 Cyg. Observed Hα emission line profiles are single-peaked in all three knots, although they differ in width: the FWHM is about 50 km s^{-1} for knots A and B and about 100 km s^{-1} for knot C. The radial velocities of these knots differ even more drastically. While knots A and B have $V_r = -40$ km s^{-1} and -93 km s^{-1} respectively, the radial velocity of HH 381 C is $+172$ km s^{-1} (see also right panel of the Fig. 2 to compare the relative positions of the HH knots). This last value ideally corresponds to the velocity of the V2494 Cyg counter jet (see sec. 3.3) and actually confirms that HH 381 C indeed belongs to the southern lobe of the V2494 Cyg outflow, along with the fainter HH knots HH 382 E, F, G (Magakian et al. 2010) and the disrupted HH 382 A-D group at the head of the southern outflow. All of these objects lie almost precisely on a straight line that coincides with the axis of the nebula. However, knots HH 381 A and B must belong to some other outflow, as has previously been suspected based on their location. This is further supported by the morphology of the knots: HH 381 C looks like a small bow shock heading southward, while the shapes of HH 381 A and B do not show marked symmetry.

As was mentioned above, we were able to obtain the slit spectrum of knot HH 382 A. The spectrum is typical of HH objects, with Hα, [SII] and [OI] emission and no traces of continuum. The line intensities correspond to low density and moderate excitation. The radial velocity of this knot is rather low ($+23 \pm 17$ km s^{-1}) but is positive, which confirms that the HH 382 A-D group is the leading part of the southern flow (at least in the optical range). Taking into account its distance from the source and disrupted appearance, such a low velocity is not surprising.

4 DISCUSSION

4.1 The Star

The central star V2494 Cyg was detected in the 2MASS survey as the object 2MASS J20582109+5229277 with the following photometric values in the three near-infrared bands: J=11.54±0.031, H=9.81±0.030 and K=8.31±0.017 mag. The estimate of the interstellar extinction ($A_V = 5.8$ mag), taken from the map of Rowles & Froebrich (2009), places V2494 Cyg in the locus of T Tau stars in the two-colour diagram (Rydgren & Vrba 1983; Meyer & Calvet 1997). Even without the application of the extinction correction we see that V2494 Cyg is located among other FU Ori-like objects in this diagram (see Greene, Aspin & Reipurth 2008 and Aspin et al. 2009). But the bolometric luminosity of V2494 Cyg, estimated from IRAS fluxes (Reipurth et al. 1993), is quite low for a FUor. The distance controversy leads to a wide range of estimates: from 14 L$\odot$ (D=700 pc, Reipurth & Aspin 1997) to 45.55 L$\odot$ (D=1300 pc, Connelley, Reipurth & Tokunaga 2007). For 800 pc, as is assumed in our works, this approach yields 18 L$\odot$.

Nevertheless, there are many arguments in favour of V2494 Cyg, formerly HH 381 IRS, being a genuine FU Ori type object.

Its infrared spectrum is virtually identical to other FUors (Aspin et al. 2009).

Its optical spectrum shows wide and blueshifted Hα absorption (though seen only in reflection as described in sec. 3.4) and some other features typical of FUors.

Its increase in optical brightness was actually observed; it remains at maximal brightness for more than 20 years.

Its spectral type can be estimated as G (in the region near Hα).

There is no detected Fe II or Fe I emission in the optical spectrum, typical for T Tau stars and EXors.

Nevertheless, several properties of this star make it a rather unusual FUor.

The amplitude of the outburst is only $\approx$ 2.6 mag in R (however, if the R1 magnitude in USNO-B is also overestimated, it will make the amplitude larger and more similar to classical FUors).

Its post-outburst bolometric luminosity is quite low.

The object is the source of a giant parsec-sized bipolar flow. On the other hand, even if some of the known FUors are related to HH objects, only a few of them possess jets and develop extended outflows.

Rather strong forbidden emission lines are observed in the spectrum of the star. Even if we assume that they all originate only in the jet, this is not typical of FUors.

In fact, V2494 Cyg is already included in the list of 10 known FU Ori type objects with the outburst detected (Reipurth & Aspin 2010, V2494 Cyg is referred to as HH 381 IRS in this paper) but among them there are no other objects with so strong emission. We will return to this question below.

Another nearly unique feature of V2494 Cyg and its nebula is the pronounced "spectral asymmetry" (by which we mean that the spectra of the star observed directly and through reflection show marked differences). This asymmetry is the direct result of the existence of the anisotropic expanding stellar envelope around the central star combined with the geometrically favorable projection of its spectrum on the walls of the cavity in the interstellar dust (we see these walls as the bright conical nebula, which reflect the spectrum of the envelope at various latitudes in the line-of-sight direction). Besides the classic example of R Mon (Jones & Herbig 1982), more or less well studied cases include RNO 129 (Movsessian & Magakian 2004) and PV Cep (Movsessian et al. 2008). The object V2494 Cyg, however, is the first FUor in this group, which makes it even more intriguing. First of all, it confirms that we observe this star near its equatorial plane where the influence of the outflowing envelope is minimal; this implies that FUors with the most prominent P Cyg absorptions should be oriented nearly pole-on. In addition, it gives a chance to analyze the structure of the envelope, similarly to R Mon (Magakian & Movsessian 1997), and to compare it with theoretical predictions. Spectropolarimetric studies of this nebula will be very useful in separating the reflected and *in situ* produced spectral lines.

4.2 Outflow

The outflow of V2494 Cyg can be considered to be a typical parsec-sized outflow. However, such long flows are unusual for FUors. Among all known FUors and FUor-like objects only L 1551 IRS5 (which most closely resembles V2494 Cyg, also taking into account the very low luminosity of both central stars), Z CMa (although it is not known yet if this flow is produced by the FUor or its more massive companion) and the recently found neighbor Braid star (also called HH 629 IRS or V2495 Cyg) possess such well-developed optical flows. Furthermore, this outflow is the most extended of all those listed above - more than 7 pc in full span in the optical. With its probable molecular hydrogen extensions, described in detail by Khanzadyan et al. (2012), it may extend even to 9 pc. Here we should mention also that V2494 Cyg drives an extended N-S molecular outflow, de-

tected in the radio wavelength range (Moriarty-Schieven et al. 2013, in preparation).

It is obvious that such a long flow should have a significant age, which can also be inferred from the disrupted morphology of its leading bow shocks (Magakian et al. 2010). In this previous work, the kinematic age of 17,600 years was given for its most distant optical bow shock HH 967. This estimate was based on the assumption of 200 km s^{-1} for the mean velocity of the outflow and 800 pc for the distance. For the preceding molecular hydrogen clumps the age will exceed 20,000 years. However, such age estimates for the V2494 Cyg flow are very approximate because, on the one hand, the ejection velocity can be far underestimated (see Sect. 3.3) and, on the other hand, the outflow probably decelerates (Sect. 3.5). In any case, the age of the V2494 Cyg outflow should be at least about 10,000 years (probably much more: in the paper of Khanzadyan et al. 2012 it is shown that it can reach even 10^5 years). Thus, it originated long before the detected recent outburst. Just the same situation exists for the neighbor V2495 Cyg (formerly known as the Braid star) and its outflow (Khanzadyan et al. 2012).

One should keep in mind that V2494 and V2495 Cyg are so far the only known FUors with observed recent eruptions *and* extended high-age flows. However, these remarkable examples still cannot differentiate between various mechanisms which have been suggested to explain the FU Ori phenomenon. The hypothesis that FU Ori outbursts should be directly connected with extended outflow formation, proposed several tens of years ago (Dopita 1978; Reipurth 1989) seems very attractive (see also Reipurth & Aspin 2010). Yet we actually have no direct evidence: extended outflows can be the independent manifestations of the strong accretion during PMS stellar evolution. However, in any case multiple paired knots can be considered as evidence of the periodic eruptive character of mass-loss events (Reipurth & Bally 2001). The recent analysis of the morphology of nearly 30 molecular outflows by Ioannidis & Froebrich (2012) confirmed the estimates, made from optical studies, namely that the typical time gaps between the significant ejections in the outflow are of the order of 10^3 years. Meanwhile, the time between recurrent FU Ori outburst events is believed to be about 10^4 years (Hartmann & Kenyon 1996; Reipurth & Bally 2001). Hence, they seem in closer agreement with the total outflow lifetime. However, the absence of an object with two observed recurrent FU Ori outbursts makes all these indirect estimates highly speculative.

Nevertheless, the discovery of a jet in the immediate vicinity of V2494 Cyg makes the situation even more intriguing. Estimating from our spectrograms the visible length of the jet (and counterjet) as 4 arcsec, we get its kinematical age as about 40 years (for the 400 km s^{-1} as ejection velocity). This value is in the good agreement with our estimation of the probable date of the eruption (with all the caution about the uncertainties both in the eruption date and the jet age) and, in turn, implies that the jet started to propagate near the moment of the V2494 Cyg outburst. To our knowledge, such a direct connection is found here for the first time. It can be considered as the first direct proof that the FU Ori outbursts create collimated jets (at least in some cases: of course, we cannot state that *all* FU Ori events produce directed outflows). Taking into account the rather large kinematical age of the full V2494 Cyg outflow, one can

go further and suggest that its distant and disrupted bows were created during one or even several (depending on the age estimates) previous FU Ori events in V2494 Cyg, thus making this star the first proven recurrent FU Ori object.

Another interesting feature is the different velocity gradients for the lines of higher and lower excitation level in the jet and the counterjet. The more or less similar behavior of emission lines was found in the small HH knot HH 214 in the GM 1-27 nebula (Magakian & Movsessian 1995). One can suggest that the Hα and [NII] emission traces the high-velocity/high-density axis of the jet, while the [SII] and [OI] lines are excited in entrained gas that is steadily accelerated by the jet. Of course, other explanations are not excluded. Yet another feature of interest is the definite multi-component structure of the forbidden line profiles. This perhaps can be understood if we assume that the jet itself consists of several tiny knots of various excitation level which are not yet well separated. The existence of the very high velocity and high density component just within 1 arcsec of the star supports this suggestion to some extent. It can even be the indication of a new ejection. A similar single high-velocity knot, seen in forbidden lines, was detected in the outflow of LkHα 324SE (Herbig & Dahm 2006).

Concerning the origin of the HH 381 A and B knots, their radial velocity data definitely reject their affiliation with the extended N-S flow from V2494 Cyg. Thus, they likely belong to some other flow. One still can return to the suggestion made in our previous paper (Magakian et al. 2010), that these knots are either produced by the hypothetical companion of V2494 Cyg (the only argument for this is their proximity) or that they correspond to the western lobe of the extended flow from IRAS 20573+5221.

We reach the conclusion that the combination of all the features discussed above indeed makes V2494 Cyg a unique object even among so rare a class as FUors.

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