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Search for Massive Planets in the Disks of FU Orionis Objects

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Abstract FU Orionis systems are young stellar objects undergoing episodes of enhanced luminosity, which are generally ascribed to a sudden increase of mass accretion rate in the surrounding protostellar disk. Models invoking a thermal instability in the disk are able to reproduce many features of the outburst, but cannot explain the rapid rise time-scale observed in some cases. The rapid-rise outbursts can be a natural consequence of the existence of a massive planet formed in the disk. Periodic variations of the Hα line profile observed in FU Ori, the brightest member of FU Orionis class, can be indicative of the presence of a massive planet orbiting in the disk at a distance of $\sim 12\,R_{\odot}$.

Key words: techniques: spectroscopic – stars: pre-main sequence – stars: individual: FU Ori

1 INTRODUCTION

Radial velocity surveys (Marcy & Butler 2000) show that the frequency of massive planetary companions to late F and G dwarf stars on main sequence is about 6%. In particular 1% of surveyed stars possess *hot Jupiters*, that is, massive planets within 0.1 AU from their parent star (Butler et al. 2000). According to planetary migration theories (Lin & Papaloizou 1986; Lin et al. 1996) the abundance of such planets could be considerably higher in pre-main-sequence stars with a significant fraction of T Tauri stars harboring planetary companions at relatively small orbital radii. Directly detecting planets around T Tauri stars is very difficult. The searches for planetary transits have to contend with additional photometric variability due to rapid rotation on a time scale of a few days, whilst the radial velocity methods cannot be applied due to the strong veiling present in the stellar absorption features.

The subset of accreting pre-main-sequence stars known as FU Orionis (FUor) objects can present a good opportunity for searching for hot Jupiters. These objects undergo violent and probably recurrent outbursts, during which they can increase their bolometric luminosity by two to three orders of magnitude. These outbursts are generally attributed to a sudden increase of the mass accretion rate ($\sim 10^{-5} \div 10^{-4}\,M_{\odot}\,\mathrm{yr}^{-1}$) in the disk of an otherwise normal T Tauri star. Lodato & Clarke (2004), following the suggestion of Clarke & Syer (1996) that the outburst is triggered by the presence of a planet embedded in the disk, developed a simple one-dimensional time-independent outburst model. This model is able to reproduce the observed outbursts with a planet mass of $10 \div 15\,\mathrm{M_{Jupiter}}$.

Clarke & Armitage (2003) have suggest that a planet embedded in the disk of a FUor object would lead to a clear spectroscopic signature in the form of a periodic modulation of the double–peaked line profiles observed in these systems, with periods corresponding to the orbital frequency of the planet. Periodic modulations (with a period of ≈ 3 days) in the line profiles of FU Ori (Herbig et al. 2003) seem to confirm this suggestion. In this paper we point out that the Hα variability of FUor objects can be used as a powerful diagnostic for the detection of massive planets in their disks.

2 BASIC MULTIFREQUENCY PROPERTIES

The FUor phenomenon represents a rare and not yet fully understood phase of the early evolution of the low-mass stars. FUors share a distinctive set of morphological, photometric and spectroscopic characteristics.

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Most have fan-shaped or coma-shaped reflection nebulae on optical and near-IR images.

Photometrically FUors are characterized by violent and probable recurrent outbursts, during which the stars can increase the bolometric luminosity by two to three orders of magnitude. The light curves (Fig. 1) of the three best studied FUors (i.e. FU Ori itself, V 1515 Cyg and V 1057 Cyg) show remarkable differences between each other. The rise time–scale of FU Ori and V 1057 Cyg is very short (of the order of 1 yr), while that of V 1515 Cyg is definitely longer ($t_{\rm rise} \approx 20$ yr). On the other hand, while FU Ori and V 1515 Cyg have a very long decay time-scale ($t_{\rm decay} \approx 50 \div 100$ yr), V 1057 Cyg decays much faster ($t_{\rm decay} \approx 10$ yr).

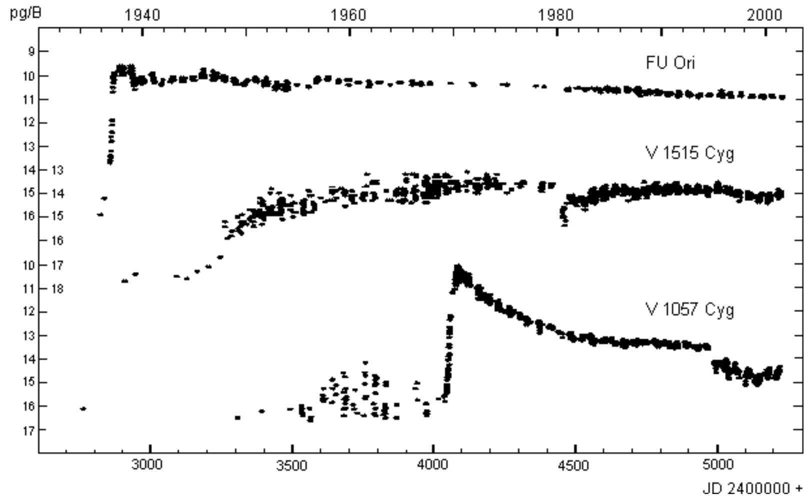

Fig. 1 Optical light curves of the three best studied FUors (Clarke et al. 2005 and references therein).

A number of objects are known that are spectroscopically similar to FUors, but for which the outburst phase has not been documented. Quite possible, these represent objects whose outbursts occurred too long ago to have been observed.

Spectroscopically, FUors have no-emission-lines spectra with optical characteristics of G-type supergiants, yet near-IR characteristics of cooler K- or M-type giants/supergiants dominated by deep CO overtone absorption.

All FUors have broad optical or IR absorption lines or both indicating large rotational velocities. The near-IR CO lines have significantly smaller rotational velocities than the optical lines. Many FUors display doubled absorption lines on optical and near-IR spectra. The long-term stability of the doubled absorption lines indicates that the lines are not produced by two stellar components in a binary system.

All FUors show large excesses of radiation at both UV and IR wavelengths. The near-IR excess is clearly photospheric in origin, because the CO and H_2O absorption features are very strong. The UV excess appears associated with an A- or F-type photosphere, that is hotter than the G-type photosphere observed at longer wavelengths. In addition to significant far-IR and submm emission, many FUors are strong radio continuum sources at cm wavelengths.

All of the optically bright FUors ($A_{\rm v} \sim 2 \div 3$ mag) have very strong winds, as indicate by the very broad, deep P Cyg absorption profile seen in the Balmer lines and the low-ionization Na I resonance lines. Typical values for the terminal velocity and the estimated mass loss rate are $V_\infty \sim 300 \div 500$ km s^{-1} and $\dot{M} \sim 10^{-5} M_\odot$ yr^{-1} respectively. The Hα emission component is normally absent or weak. The Hα line profile can change on month to year time scales (Bastian & Mundt 1985; Croswell et al. 1987; Welty et al. 1992). Furthermore daily variations of Hα line profile were observed in FU Ori (D'Angelo et al. 2000).

The embedded FUors ($A_{\rm v} \geq 10$ mag) drive large-scale molecular outflows and bipolar HH outflows.

Finally, FUor eruptions must be repetitive (Herbig 1977; Hartmann & Kenyon 1985). The event statistics of known FUors suggest that a young star must undergo $10 \div 20$ FUor eruptions before reaching the main sequence. This estimate may be a lower limit because some outbursts have certainly missed. Reipurth's proposal that FUor eruptions produce HH objects suggests a recurrence time scale of ~ 1000 yr, based on the identification of multiple bowshocks (ejection events) with dynamical separations of $500 \div 2000$ yr (Reipurth 1985, 1989; Hartigan et al. 1990; Reipurth & Heathcote 1992; Bachiller et al. 1994). The discovery of giant HH flows with dynamical time scales of $10^4 \div 10^5$ yr (Reipurth et al. 1997) allows $10 \div 100$ eruptions, if eruptions actually power the outflow.

3 MECHANISMS OF OUTBURST

According to Hartmann & Kenyon (1985) the FUor outbursts are due to a sudden increase of the mass accretion rate (up to $10^{-4}\, M_{\odot}$ yr^{-1}) in the disk of an otherwise *normal* T Tauri star. This interpretation is suggested by a number of observations:

1. in one case (i.e. V 1057 Cyg) a pre-outburst stellar spectrum is available, it shows typical features of a T Tauri star;
2. the spectral energy distribution (SED) after the outburst is well described in term of accretion disk SEDs;
3. optical and near-IR line profiles are usually double-peaked, as one expects if the lines originate from a differential rotating disk;
4. the gradual decrease in the rotational velocity with increasing wavelength occurs because the longer wavelength emission is produced in more slowly-orbiting material at larger disk radii than the more rapidly moving disk material responsible for the short wavelength emission.

The disk model fails to explain $10 \div 100\, \mu$m SED of many FUors, but the disagreement can be due to the fact that the mid-IR radiation is optical light absorbed and reradiated by a surrounding envelope. However, there are still several unsolved issues where observations and model predictions do not match. In particular, according to Herbig et al. (2003) FUors represent a special subclass of rapidly rotating T Tauri stars.
Several different mechanisms have been suggested to trigger the outbursts:

1. a tidal interaction with a companion star (Bonnell & Bastien 1992), this model is supported by the existence of some binary systems among FUors;
2. a gravitational instability in the outer massive disk (Armitage et al. 2001), according to this model the outburst duration is $\sim 10^4$ yr, two order of magnitude longer than the observed ones;
3. a viscous thermal instability (Bell & Lin 1994) in a disk feed at high mass accretion rate from a surrounding envelope, according to this model the disk tends to become unstable at the inner edge, then the instability propagates inside out, producing a slowly rising luminosity compatible with the light curve of V 1515 Cyg. This model cannot explain the rapid time-scale of FU Ori and V 1057 Cyg. In order to obtain a rapid rise, the instability must be first triggered at a large radius, so that the instability propagates outside in.

According to Clarke & Syer (1996) outside-in disk instabilities are a natural consequence of the existence of protoplanetary/protostellar companions. The protoplanetary/protostellar companion would be formed through gravitational instability on a dynamical time-scale of $\sim 10^5$ yr, and, provided that it is was formed al less than a few AU, it would be swept in to $\sim 15\, R_{\odot}$ in less than 10^5 yr. A companion of mass $10^{-2}\, M_{\odot}$ at this radius would act as a flood gate which stores material upstream and periodically releases it following the ignition of the thermal ionization instability.

Lodato & Clarke (2004) explored the possibility that the thermal instability is triggered away from the disk inner edge (at a distance of $\approx 10\, R_{\odot}$ from the central star) due to the presence of a massive planet embedded in the disk. This planet would lead to a clear spectroscopic signature in the form of a periodic modulation of the double-peaked line profiles observed in FUors with periods corresponding to the orbital frequency of the planet (Clarke & Armitage 2003). Periodic modulations ($P \approx 3$ days) in the absorption line profiles of FU Ori were observed (Herbig et al. 2003).

4 Hα VARIABILITY

In an extensive campaign of spectroscopic observations carried out on the three well studied outbursting FUors (i.e. FU Ori, V 1057 Cyg and V 1515 Cyg), we revealed strong variations of the Hα P-Cygni line.

A sample of these observations is shown in Figures 2 and 3. Similar variations were detected in FU Ori and V 1057 Cyg (see figs. 25 and 26 by Herbig et al. 2003). There is no correlation between the changes of the absorption and emission components.

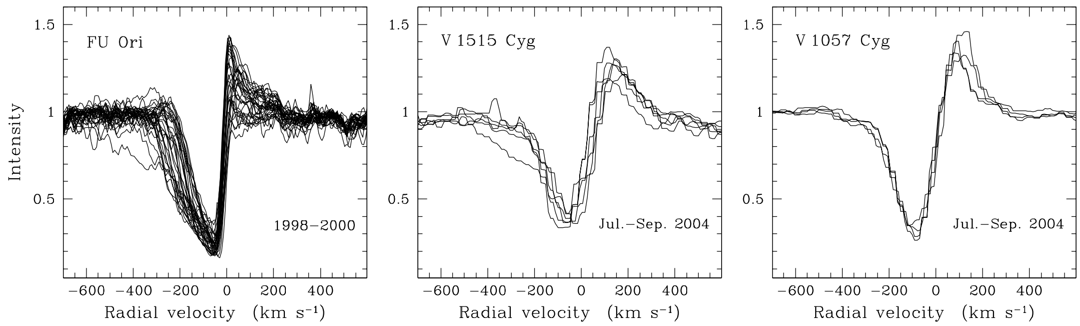

Fig. 2 Variations of the Hα profile of FU Ori, V 1057 Cyg and V 1515 Cyg.

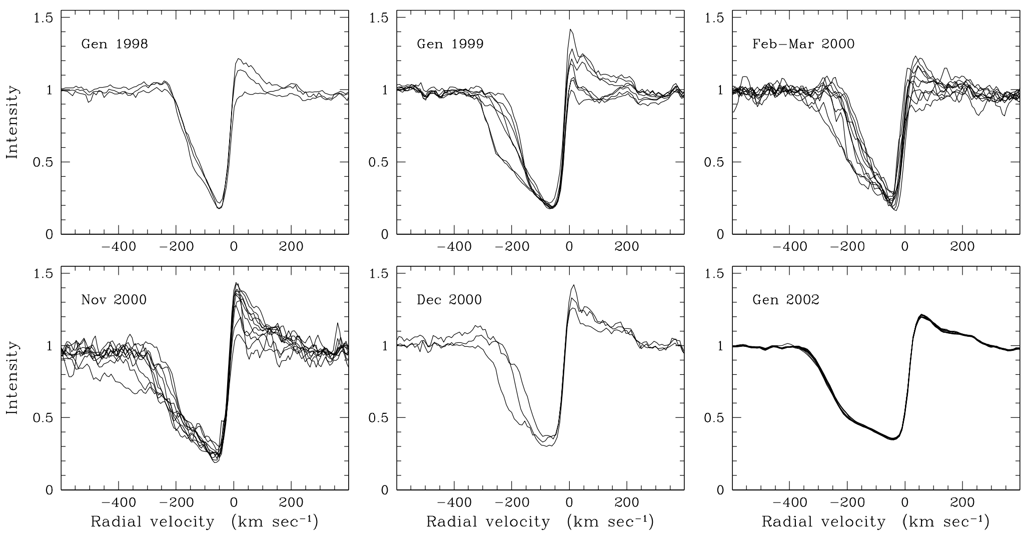

Fig. 3 Variations of the Hα profile of FU Ori in different epochs.

The dense time coverage of our spectroscopy on FU Ori makes feasible a search for periodicity. The time series analysis (Scargle 1982) was used to search for periodicity in Hα absorption and emission components. No periodicity is present in Hα absorption component. On the contrary, Hα emission component shows a periodicity of 6.70 days (Fig. 4). A periodicity of 14.8 days was found in Hα absorption component by Herbig et al. (2003) in 1997–98, but it disappeared by 2000.

5 DISCUSSION AND CONCLUSIONS

To explain the presence of emission components in the Hα, Na I D, Ca II k and Mg II h, k lines, D'Angelo et al. (2000) had to introduce in the FU Ori disk atmosphere a thin layer with temperature inversion at the wind base (like a chromosphere). They were able to reproduce the observed Hα profiles in the spectrum of FU Ori with a reasonable accuracy. D'Angelo et al. (2000) interpreted the observed variations of the Hα profile as resulting from axisymmetric variations in the physical parameters of the wind or, to be more precise, in the temperature and velocity distributions along wind stream lines.

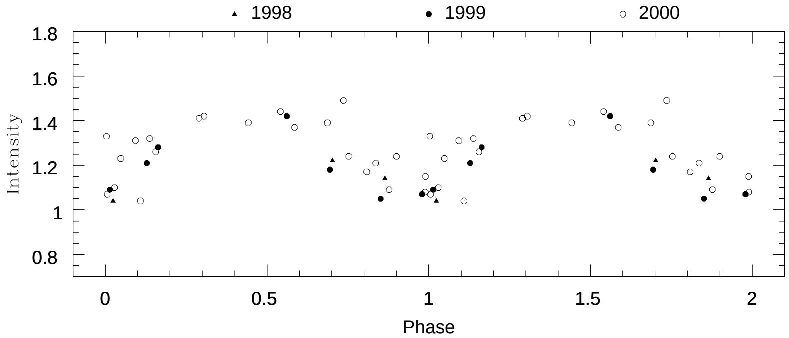

Fig. 4 Phase diagram of the Hα emission component of FU Ori for a period of 6.70 days.

In the frame of this scenario the 6.70 day period of the Hα emission component can be indicative of a periodic variability of the thermodynamic state of a chromosphere-like thin layer, reflecting a thermal instability in the disk (see Fig. 4). This instability may be due to effects of mass accretion of a massive planet in the disk. The Hα emission component behaviour can be also explained by a periodic occultation of the redshifted material due to the presence of a low mass companion in the disk. If the central star has a mass of 0.5 $M_{\odot}$, the period of 6.70 days corresponds to a keplerian rotation at distance of 11.8 $R_{\odot}$. If this period will be confirmed by new extensive campaigns of observations, the Hα variability of FUor objects can be considered as a new spectroscopic diagnostic for the detection of massive planets in their disks.

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