Confirmation of Periodic Variability in FU Orionis

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Abstract

High-resolution spectra of FU Ori were taken from the SOPHIE échelle spectrograph at the 1.93m telescope at Haute Provence Observatory over a series of 21 nights in 2007. The analysis of the optical line profiles confirms periodic variations previously seen in radial velocity by Herbig et al. (2003). Two spectral regions, 6144-6187Å and 5549-5654Å both showed photospheric line variability on a period of 3.56 and 3.63 days respectively. The nature of the detected variation was compared with the predictions arising from the signature of a hot Jupiter. If an FU Orionis object had a hot Jupiter embedded in the disk, this would manifest as time-dependent non-axisymmetric distortions in the optical line profiles, sustained over different epochs. When phase folded with the detected periods, the blueward wing and the redward wing were found to be in phase, indicating a possible bar-like structure which has been sustained over a decade.

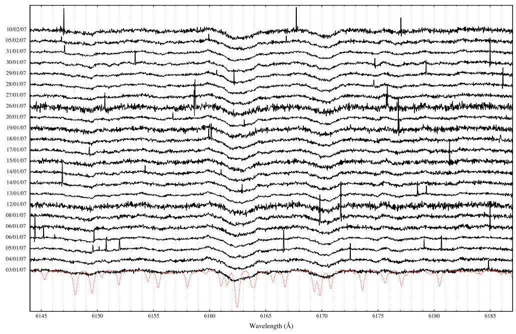


Figure 1. Raw spectra taken from the SOPHIE cross-dispersed échelle spectrograph at the 1.93m telescope at Haute Provence Observatory over 21 nights are shown in black with the template used in the cross correlation shown in red.

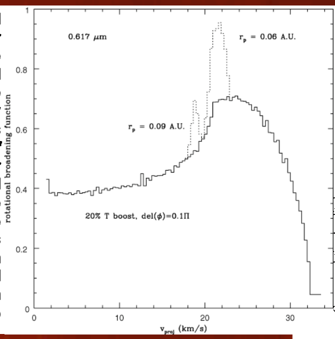


Figure 2. Rotational broadening function for absorption lines in the spectral region centered on 6170Å. The normalisation is arbitrary and half the line is plotted (the other half would be the mirror image of the unperturbed profile, shown by the solid histogram). The dotted histograms correspond to models in which a 'planet' is placed at radii indicated. Taken from Clarke et al. (2003)

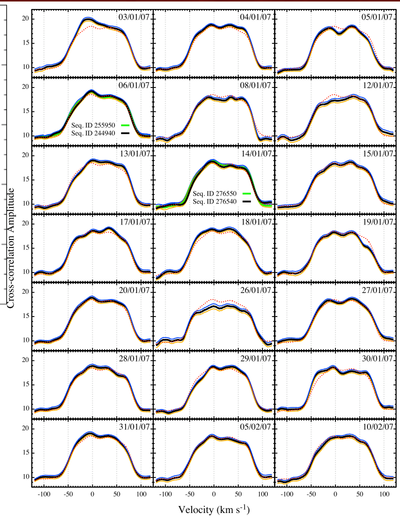
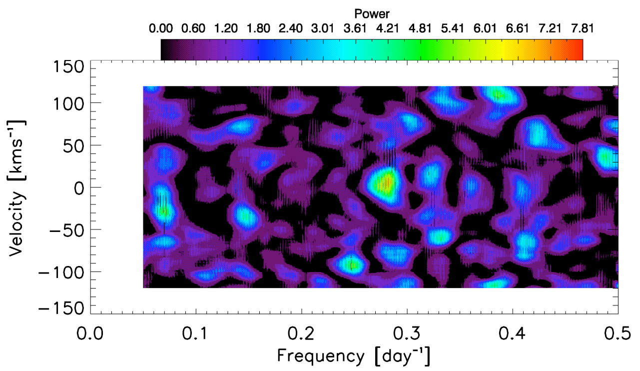


Figure 3. Cross correlations for each observation in the 6144-6187Å region are shown with the black lines, with the upper and lower 3σ errors shown by the dark and light blue lines accordingly. When two observations were taken in one night a dark green line is used to represent the additional observation. The average cross correlation over all epochs is shown by the red dashed line.

Introduction

FU Orionis objects represent a small class of pre-main-sequence stars, originally classified by a large increase in optical brightness of ~4 magnitudes or more due to long periods of rapid accretion in their protoplanetary disks. This class provides a unique opportunity to observe the inner circumstellar disk in optical light. Although FU Orionis objects represent a small unique class of young stellar objects, understanding the phenomenon would benefit not only stellar evolution, but also planet formation theories. Planetary migration theories suggest the abundance of hot Jupiters could be considerably higher in pre-main-sequence stars. Lodato et al. (2004) suggested that an embedded planet in the disk could potentially trigger the rapid rise outburst of these systems. If an FU Orionis object had such a planet embedded in the disk, this would manifest as time-dependent distortions in the optical line profiles of these objects, sustained over different epochs. Figure 2 taken from Clarke et al. (2003) shows how the signature of such a planet would manifest the switching of the line profile distortions from the blue to red wing, after the existence of such a planet or hot spot dammed up the disk, leading to the instabilities necessary to generate an outburst. Herbig et al. (2003) previously found a period in the radial velocity of FU Ori of 3.54 days with a spectral resolution of 7kms^{-1}. Examination of the higher resolution data available allows more detailed examination of the profile variations and structure in the inner circumstellar disk.

Figure 4. Contour radial velocity periodogram showing the periods found in the 6144-6187Å region. The 0.01 FAP for this region was 7.476, hence the significant periods are displayed in red. The period detected was 3.56 days.

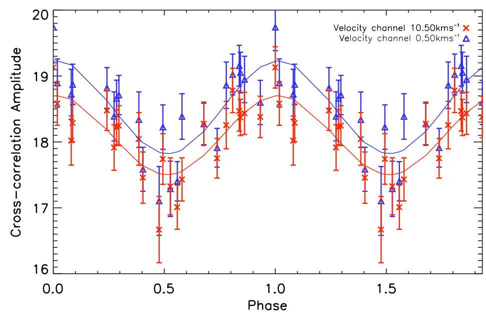


Method

The spectral resolution of SOPHIE in HR mode is R=75000. The data were continuum subtracted via median and boxcar filtering performed twice to ensure variations in the continuum were not included in the resulting line profiles. The wavelength ranges 5549-5654Å, 6144-6187Å and 6325-6449Å were selected in order to compare with previous results of Herbig et al. (2003) and Hartmann et al. (1985) and to reduce the effects from mass loss. These specific regions were chosen to be situated in relatively featureless regions of spectra, distant from the spectrograph edges to reduce contamination by edge effects. The raw continuum subtracted spectra used in the analysis of the 6170Å region is displayed in figure 1, and the G0Ib reference star, β Aqr, taken from SOPHIE is shown with the red line. Its radial velocity was found by an initial correlation with a synthetic spectrum of a G0 star with T_{eff}=6000, log g=3, and subsequently zeroed. The spectra in figure 1 were filtered for comic rays and spurious events and cross-correlated with a template G0Ib reference star, the resulting cross-correlations are shown in figure 3.

Radial velocity curves were constructed at each velocity channel sampled, and tested for a period between 2-20 days using methods describes by Scargle (1982) and Horne et al. (1986). The significance of the periods detected were tested using Fisher's method of randomisation and found to false alarm probability (FAP) of 0.01. The value of the significant period was found from the "centre of power" of all significant powers.

Figure 5. Phase diagram for the period of 3.56 days. The most redshifted velocity channel with a significant power is shown in by the red crosses with a red sinusoidal curve fit to the points giving a chi-squared of 54.81 for 43 degrees of freedom. The most blueshifted velocity channel with a significant power is shown with blue triangles with a blue sinusoidal curve fit to the points producing a chi-squared of 43.41 for 43 degrees of freedom.



Results

All the regions analysed displayed a significant period. The periodogram shown in figure 4 displays the most probable period for the 6170Å region in red of 3.56 days, which had the most significant detections with 92 significant results. The region 5549-5654Å produced a period of 3.63 days from a power weighted contribution from 47 significant results, which spanned the velocity channels at 2kms^{-1} to 8kms^{-1}. These regions confirm the period of 3.54 days found previously in the radial velocities averaged over six spectral orders (5560-7520Å) by Herbig et al. (2003), which confirms disk structure sustained over a decade. The spectral window of 6325-6449Å produced a period of 9.43 days from a power weighted calculation involving 47 significant results, which spanned the velocity channels from 110kms^{-1} to 115.5kms^{-1}, the very edge of the cross correlation window.

When the 6144-6187Å region is phased with the period detected, figure 5 shows the cyclic variations in the cross correlation amplitude in these 21 days. Figure 5 shows that the more blueward edge of the red spot in figure 4 not only has a better fit to a sinusoidal curve than the redward edge with chi-squared values of 43.41 and 54.81 respectively for 43 degrees of freedom, but also has a larger semi-amplitude of variation 0.70 to 0.60 respectively in cross-correlation amplitude. However figure 5 also shows that the more blueward and redward wing of the velocity channels displaying significant periods in figure 4 are in phase, which contrasts the theoretical models by Clarke et al. (2003), shown in figure . for that of an embedded planet within the disk. The in-phase nature of the period across the significant velocity channel suggests a bar-like structure within the disk.

References

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