Viscous Heating and Boundary Layer Accretion in the Disk of Outbursting Star FU Orionis

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FUor Stars

Young stellar objects (YSOs) are known to be around 10-100 times less luminous than expected from steady state accretion, where material is transported from the disk to the central star. This raises the possibility that accretion is not consistent across the early stages of stellar evolution, but is episodic (Kenyon & Hartmann 1995; Evans et al. 2009).

FU Ori is the archetype of an object class known to undergo rapid outbursting events. Increasing in brightness by up to 6 magnitudes over a few day period, but taking many decades to return to a quiescent state (Hartmann & Kenyon 1996; Herbig 2007). The cause of these sudden outbursts is thought to be rapid changes in the accretion rate.

As the brightest object of it's class it is fundamental to our understanding of accretion processes in young stellar objects. The unprecedented spatial resolution of our observations provide us with a uniquely detailed picture of the inner disk regions.

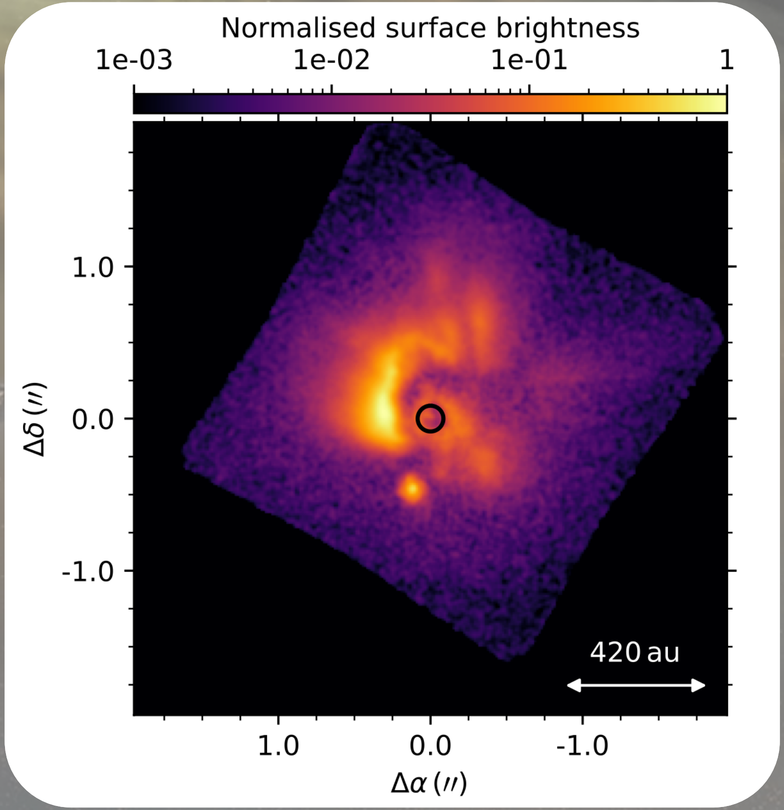

Fig 1: Linearly-polarized intensity, scattered light image obtained with the Gemini Planet Imager (GPI) in the J-band (Laws et al. 2020) The image is centred on FU Ori N within the black circle. FU Ori S is also visible to the South-West.

Observations

Observations were obtained using the MIRC-X instrument, a 6-telescope beam combiner located at CHARA (Centre for High Angular Resolution Astronomy). The CHARA array is a Y-shaped interferometric facility that comprises six 1 m telescopes. It is located at the Mount Wilson Observatory, California, and offers operational baselines between 34 and 331 m (ten Brummelaar et al. 2005). The MIRC-X instrument (Monnier et al. 2004; Kraus et al. 2018), a six-telescope beam combiner, was used to obtain observations in the near-infrared H-band (λ=1.63µm, $\Delta\lambda$=0.35µm with R=$\lambda/\Delta\lambda$=50) in 2018 and 2019.

While the majority of our observations were obtained in the H band, following recent upgrades to the MIRC-X (λ=1.10 to 1.35µm) instrument we were able to obtain the first J band interferometric data of a young stellar object. This was obtained in dual H+J mode, where longitudinal dispersion compensators (LDCs) were employed to correct for atmospheric dispersion between the two bands. These wedges of SF-10 glass were manually tracked based on atmospheric dispersion models (Berger et al. 2003).

In addition to these new observations archival data was obtained from a variety of instruments operating in the H and K bands. PTI, CLIMB, PIONIER and GRAVITY observations dating back up to two decades were employed to supplement the uv coverage and extend the wavelength range of this study.

The J Band

The J-band has been a relatively untapped resource in interferometry. The J-band has the potential to not only be used in YSO studies to examine the sublimation rims and the potential for optically-thick gas inside the sublimation radius, but also in stellar photosphere studies, as a waveband which is relatively free from molecular opacities.

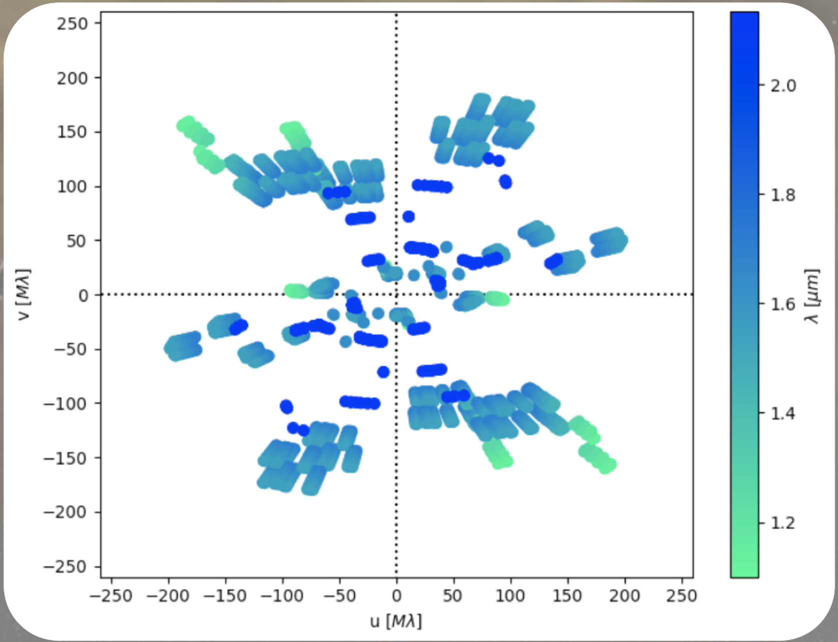

Fig 2. The uv plane of all observations detailed in Table 2. The H+J dual-band observations were obtained with CHARA/MIRC-X. The H band only observations were obtained with CHARA/MIRC-X with R=50 spectral resolution and with VLTI/PIONIER in free mode, while the K band observations were obtained with CHARA/CLIMB and PTI.

Fitting the Temperature Gradient

A temperature gradient model (TGM) allows for the simultaneous fitting of interferometric and photometric observables. It is built up by several rings extending from an inner radius R_{in} to an outer radius R_{out}. Each ring is fitted to a temperature and hence a flux value, meaning an SED can be created by combining the resultant blackbody distributions for each of the concentric rings.

$$T_R = T_0(R/R_0)^{-Q}$$

Where T_0 is the temperature at the inner rim of the disk R_0, and Q is the exponent of the temperature gradient (Kreplin et al. 2020; Eisner & Hillenbrand 2011). Our modelling finds an inclination of 32±4° and a minor axis position angle of34±11° measured East from North. We find a inner disk radius of 0.015±0.01 au with a temperature of 5700±700 K and an exponent of Q=0.74±0.08.

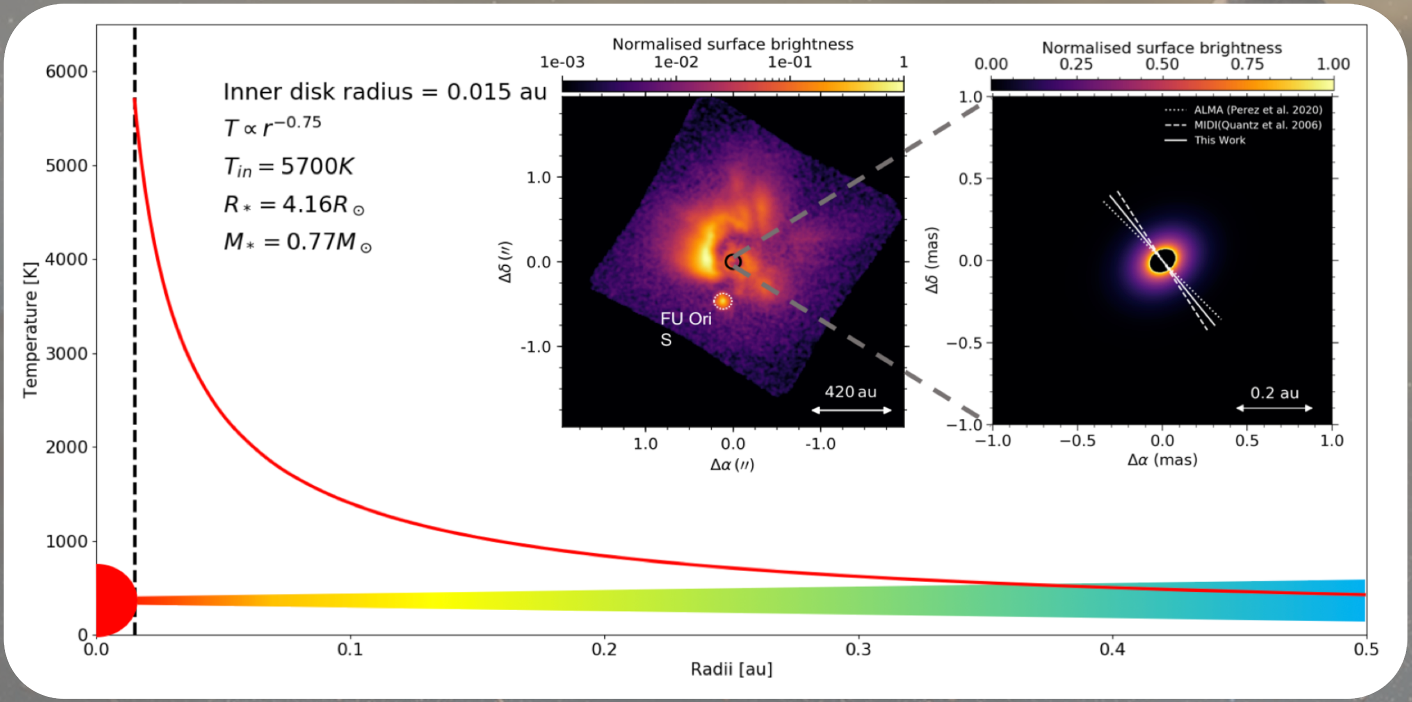

Fig 3. MAIN PLOT: Temperature Gradient of FU Ori, from disk truncation radius to 0.5 au. The dashed line represents the inner disk edge. The schematic below shows the temperature profile of the disk. The vertical height of this schematic is not to scale. INSERT (LEFT): As Figure 1 INSERT (RIGHT): Zoom in on the inner regions covered by this work, the brightness distribution of the TGM in the J band. The colours area logarithmic scale of the normalised surface brightness. The white lines in the image represent the minor axis position angle of the disk obtained from other observations in literature and this work

Accretion and Viscosity

Circumstellar disks are heated through two primary mechanisms, reprocessed stellar radiation and viscous heating. The presence and nature of viscosity in accretion disks is a hotly debated topic, however it's presence can be inferred from the temperature gradient of the disk.

The determined power-law index of Q = 0.74 is consistent with the predicted temperature profile for a steady state, optically-thick accretion disk (Pringle 1981). A temperature gradient of this profile is only possible if viscous heating processes are present in the inner disk. Heating of flared disks by reprocessed stellar radiation alone is shown to produce temperature exponents of Q <= 0.5 (Kenyon et al. 1977; Dullemond et al. 2004). Only through viscous heating can the observed temperature profile be replicated.

The observed inner radius of FU Ori is equivalent to the expected stellar radius, meaning the disk extends down to the stellar surface. This is indicative of boundary layer accretion, where material from the disk is accreted directly onto the star, as opposed to magnetospheric accretion.

Spectral Energy Distribution

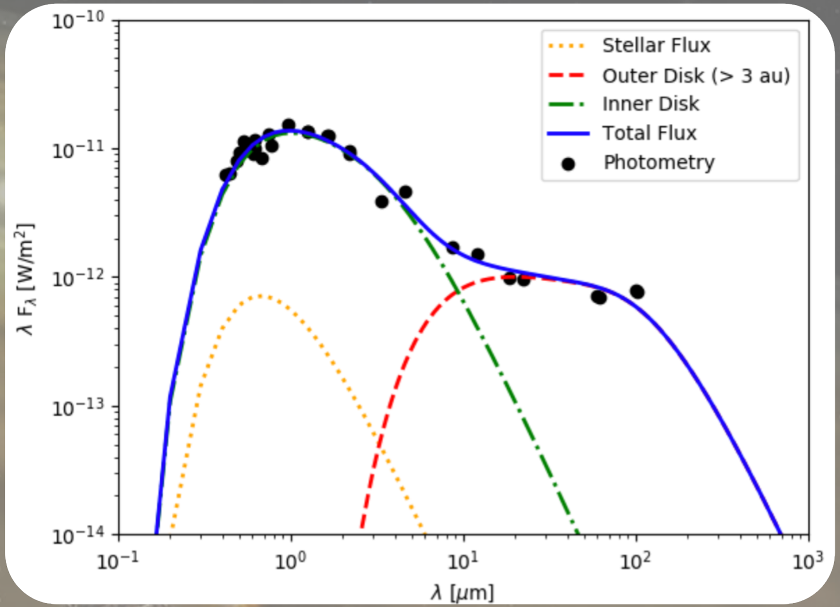

Fig 4. Spectral Energy Distribution of FU Ori. The black data represents the photometric data points. The yellow dotted line in the stellar flux contribution, the red dashed line from the outer (>3 au disk prescribed in Quanz et al. (2006). The green dash-dot line represents the contribution from the inner disk, described here as a temperature gradient model. The blue line is the total flux, a sum of all components.

Conclusions

Temperature gradient models find an inner disk that extends down to the stellar photosphere at 0.015 au where the temperature reaches 5800 K. This is in agreement with a heavily accreting star such as outbursting FUors and indicates boundary layer accretion processes. The temperature of the inner disk falls off with a power-law $T \propto R^{-0.74\pm0.02}$. This is consistent with theoretical work for steady state, optically-thick accretion disks. Such a temperature profile is only possible if viscous heating processes are present in the inner disk.