Looking close at FU Orionis' disk in the mid-infrared with MATISSE/VLTI

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The case of FU Orionis

FU Orionis is the archetype of a class of YSOs (FUors) that have experienced eruptive events due to increased mass accretion (as high as 10^{-4} $M_\odot$/yr) flowing from the circumstellar disk onto the protostar. The inner accretion disk is subsequently heated by these eruptions, leading to short-period brightenings ($\Delta B \sim 6$ mag in FU Ori within one year; Fig. 1) with long-term fading rates. The FUors group consists currently of more than 20 stars, while it is yet unclear whether they constitute a typical step in early stellar evolution. FUors are ideal laboratories in studying the evolution of disks within a few years after an eruptive event.
As the archetype, FU Orionis's disk is a well-studied object. Recently, NIR scattered light images [1,2] suggest that the size of the disk is ≤ 0.3", or else its radius~ 60 au at the adopted *Gaia* EDR3 distance (402.3 pc). Moreover, those images revealed a spiral-like arc, while ALMA sub-mm observations [3] tentatively suggested a link between the rotating disk and the arc feature. Motivated by these results, we opted to look at disk structures in L and N bands with MATISSE, the new imaging instrument of the VLTI.

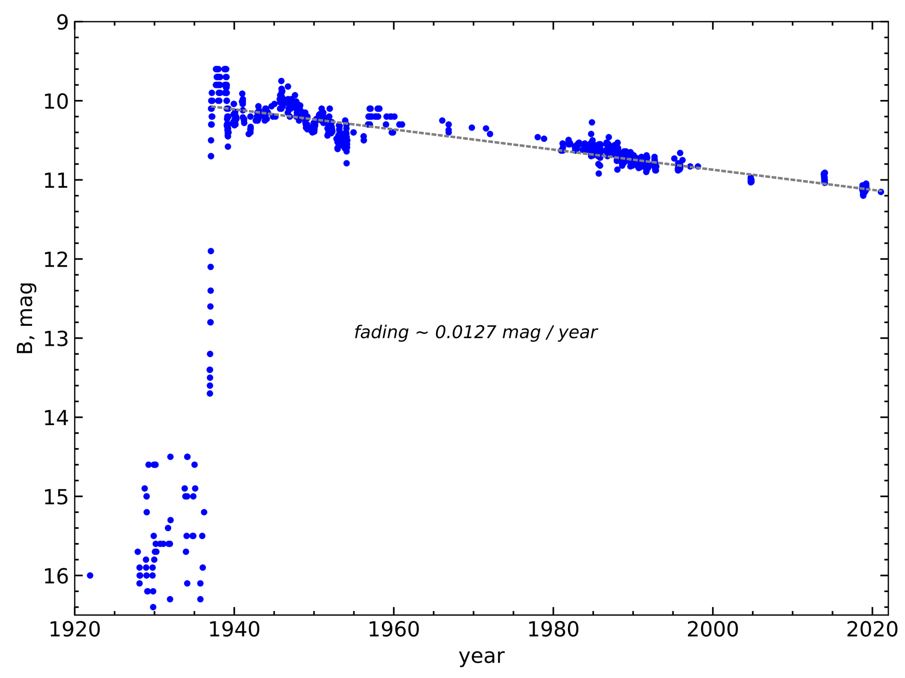

Fig.1: The historic B-band lightcurve of FU Orionis. The fading rate was estimated based on a linear fit to the data from 1937 to 2021.

MATISSE/VLTI

Snapshot interferometric observations were obtained in January 2021 with MATISSE [4], the 4-beam recombiner instrument on the Very Large Telescope Interferometer (VLTI) that operates in the mid-infrared: in L ($R \sim 30$) with the "large" (A0-G1-J2-J3) 1.8-m Auxiliary Telescope (ATs) configuration in GRA4MAT mode, and in N ($R \sim 200$) with the 8.2-m Unit Telescope (UTs) array (cf. Fig. 2 & 3). The expected spatial resolution at the longest baseline sampled ($B \sim 130$m) is 3 and 8 mas in L and N, respectively. By fitting 2D Gaussian distributions to the N-band data, we derive a MATISSE orientation for the disk with an inclination $i = 55 \pm 15$ deg and a minor axis $P.A. = 15 \pm 25$ deg, which are quite similar to earlier MIDI results [5].

Radiative transfer modeling

The interpretation of the MATISSE snapshot observations is model-dependent. We employ the radiative transfer tool RADMC3D [6] to simulate FU Ori's disk. Here, the disk density profile is described by a power-law distribution that is dependent on the disk's scale height $H(r)$, the latter being also described by a power-law, $H(r) \sim r^q$ whereby its index q is known as the *flaring* of the disk. We simulate the disk with two components: one for the hot, inner accretion disk which is represented as *grey* material, while for the cooler, passive disk we adopt a *silicate* content as in ref.[5].
The **flaring index** for the inner and passive component respectively is 1.125 and 1.17. We test two disk orientations, one derived from MATISSE (see left panel), and the other from direct measurements by ALMA [3], that is $i = 37.7^o$ and $P.A. = 43.6^o$. In both cases, the **inner disk's outer radius** can be fixed at 0.3 au (and thus smaller than in previous estimates, eg. ref.[7]), while the **dusty disk's outer radius** is roughly set at 100 au based on the NIR scattering results [1,2]. These provided better fits for the mid-infrared to sub-mm photometry. With these parameters fixed, we can fit the newly-obtained optical & NIR photometry (SAAO & NOT) by adjusting the **mass accretion rate** and the **inner disk's inner radius** at 1.64×10^{-5} $M^2_\odot$/yr and 2.33 $R_\odot$ for the MATISSE orientation, and at 0.85×10^{-5} $M^2_\odot$/yr and 1.98 $R_\odot$ for the ALMA orientation. As shown in the figures below, it appears that the ALMA orientation provides a better fit to both the SED and the MATISSE correlated fluxes.

Results

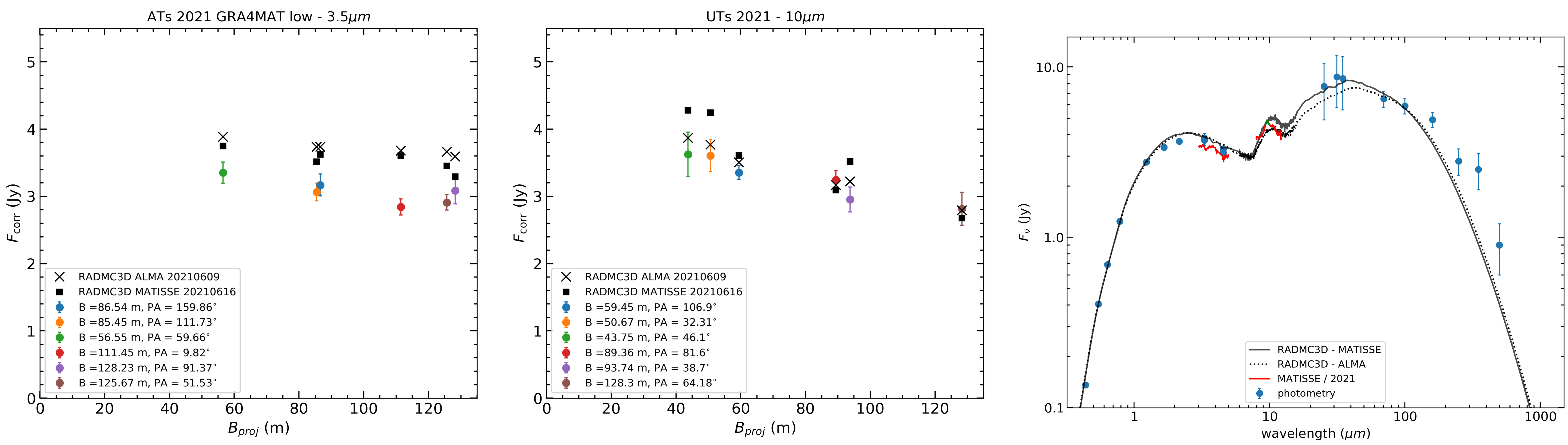

Fig.2: **Left and center:** MATISSE L-band correlated fluxes with GRA4MAT and N-band with the UTs (colored per projected baselines) against synthetic ones from RADMC3D models at 3.5 and 10μm, respectively. **Right:** Contemporary SED of FU Ori against the two RADMC3D models.

Conclusions

In this work (Lykou et al., to be submitted), we find that FU Ori's SED follows the general fading of the source even in the near- to mid-infrared, therefore we opt to fit RT simulations to the newly obtained photometry. We were able to constrain the geometry of the inner accretion and the passive dusty disk based on the new MATISSE observations and radiative transfer modelling, while we tentatively explore the case of disk misalignment between the disk structure detected by MATISSE and the earlier ALMA results. Our current results indicate that the dusty disk can be simulated better with the ALMA orientation, while adjustments are needed to further constrain the properties of the hot accretion disk. A lower limit is found for the outer radius of the hot, inner accretion disk, but this could be further adjusted as we note that currently both models overestimate the flux between 1 and 5μm (Fig.2). Furthermore, we do not find binary signatures in any of the closure phase signals (L & N data) over multiple epochs, which resemble more signals originating from inclined centro-symmetric distributions such as disks, and in that aspect we substantiate the results of ref.[8].

References: [1] Takami et al. (2018) ApJ, 864, 20 – [2] Laws et al. (2020) ApJ, 888, 7 – [3] Perez et al. (2020) ApJ, 889, 59 – [4] Lopez et al. (2014) Messenger, 157, 5 – [5] Quanz et al. (2006) ApJ, 648, 472 – [6] Dullemond et al. (2012) ascl:1202.015 – [7] Zhu et al. (2007) ApJ, 669, 483 – [8] Labdon et al. (2021) A&A, 646, A102

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