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Multi-line Diagnostics of the Interstellar Medium

Tracing episodic accretion with NOEMA: FU Orionis-type stars and their millimeter environment

O. Fehér[1,*], *Á.* Kóspál[2,3], *F.* Cruz-Saenz de Miera[2], *P.* Ábrahám[2], *M. R.* Hogerheijde[4], *Ch.* Brinch[5], and *D.* Semenov[3]

[1]Institut de Radioastronomie Millimétrique, 38400 Saint-Martin-d'Hères, 300 Rue de la Piscine, Grenoble, France

[2]Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, 1121 Budapest, Konkoly Thege Miklós út, 15-17, Hungary

[3]Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany

[4]Leiden Observatory, Leiden University, Niels Bohrweg 2, 2333 CA Leiden, The Netherlands

[5]Niels Bohr International Academy, The Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen Ø, Denmark

Abstract. The earliest phases of star formation are characterised by intense mass accretion from the circumstellar disk to the central star. One group of low-mass young stellar objects, FU Orionis-type stars (FUors) exhibit accretion rate peaks accompanied by bright eruptions in the optical and infrared regime. The occurance of these outbursts might solve the luminosity problem of protostars, play a key role in accumulating the final stellar mass, and have a significant effect on the parameters of the envelope and the disk. We are performing a systematic investigation of FUors with millimeter interferometry using NOEMA and ALMA to study the outburst events and examine whether FUors represent normal young stars in exceptional times or are unusual objects. The targeted FUors show very diverse circumstellar morphologies with envelope parameters similar to those of both Class I and Class II systems, but their disks are more massive and more compact than T Tauri disks. To shed light onto the process of disk-formation, accretion, and to what role FUors play in low-mass star-formation, we require the identification and light curve monitoring of as many of these stars as possible, together with the multi-wavelength and multi-scale mapping of their circumstellar environment.

1 Introduction

The process of low-mass star formation is the history of interstellar material accretion and infall, first during the gravitational collapse of cold, dense cloud cores, then the infall from the envelope to a circumstellar disk and the accretion of material from the disk to the surface of the forming star. Temporarily enhanced accretion events have been detected around young stellar objects as high-amplitude outbursts since the eighties [10, 11] with two historical groups of objects named after their archetype stars. One group is the so-called FUors (after FU Ori), pre-main sequence stars that show 5-6 magnitude brightness increases in the optical and IR regime, and spectral signitures indicating a rotating, accreting disk, while they

*e-mail: feher@iram.fr

exhibit an accretion rate of $10^{-4}\,M_\odot\,\mathrm{year}^{-1}$ compared to the typical rate of $10^{-8}\,M_\odot\,\mathrm{year}^{-1}$ for T-Tauri stars. The length of these FUor-type eruptions can reach years or decades, have been observed at all stages of star formation and theorized to be quasi-recurring, together with their shorter-timescale, fainter counterparts called EXor-outbursts (named after EX Ori) which show accretion rates of at most $10^{-7}\,M_\odot\,\mathrm{year}^{-1}$ during eruptions. This episodic eruption phenomenon was regarded as a possible solution for the so-called protostellar luminosity problem. The problem states that protostars are observed to be less luminous than models predict they need to be to reach the main sequence in the time available for them ([6] and references therein). However, if high-accretion rate events are recurring during their early formation, it might explain this discrepancy. The analysis of IR emission and the $10\,\mu$m silicate feature towards FUors by [9] and [16] also supported an "evolutionary sequence." In this picture, younger, more deeply embedded Class I stars (showing the silicate feature in absorption) suffer FUor-eruptions triggered by e.g. gravitational, viscous-thermal, or magneto-rotational instabilities (e.g. [2, 4]) during which a significant amount of material accretes to the star from the disk. Then the disk replenishes by infall from the envelope. After repeated outbursts and enhanced accretion rate events, the eruptions become less powerful (EXor-type outbursts) as the system develops into a Class II, T-Tauri-type star with a remnant envelope and the silicate feature in emission [17].

However, recent results have complicated our understanding of these objects and these peculiar events. Only a few dozen of FUors are known today [3], but high spectral and spatial resolution observations are revealing the large diversity of circumstellar environments present towards these stars. An ALMA study of the object V346 Nor identified a Keplerian disk and a pseudo-disk around the star, and calculations of mass infall rate from envelope to disk is higher than the accretion rate from disk to star, which could possibly trigger an instability in the disk, starting an eruption event [12]. Other examinations with ALMA showed that the circumstellar disks around FUors are both more compact and more massive than the disks around EXors and regular T Tauri stars, and a significant ratio of them (but not all) are gravitationally unstable [5, 13–15]. These findings raise interesting questions about the types of mechanisms that are responsible for triggering episodic accretion and whether the difference between FUor-disks and T Tauri-disks is intrinsic or evolutionary.

2 Eruptive young stars through millimeter interferometry

High angular resolution and high sensitivity interferometry allows us to study the morphology and kinematics of FUor-disks and envelopes. The presence or lack of an envelope can help place individual FUors into an evolutionary timeline. Since observational evidence about the frequency of FUor outbursts is limited, it is still unclear whether the bursts really occur periodically, or stochastically in time. Rather than a periodical phenomenon, structured/clumpy infalling envelopes may occasionally load extra material into the disk faster than the accretion rate onto the star, making the disk unstable and triggering a burst. Since clumpiness in the circumstellar environment is directly observable with millimeter observations, the interferometric spatial scale mapping of the envelope is a key method in clearing out this question.

Our survey with the NOEMA (NOrthern Extended Millimeter Array) interferometer consists of several observing runs starting from 2012 with the latest datasets arriving in January 2022 and covers the line and continuum emission in the 100-200 GHz frequency range of more than 16 northern FUors reaching spatial resolutions of around 1000 au. In each case, the main targeted lines are transitions of ^{13}CO and $C^{18}O$ in order to map both the more diffuse and denser gas and assess excitation temperatures, opacities and possibly column densities around the objects. On-the-fly observations with the IRAM 30 m telescope are merged to

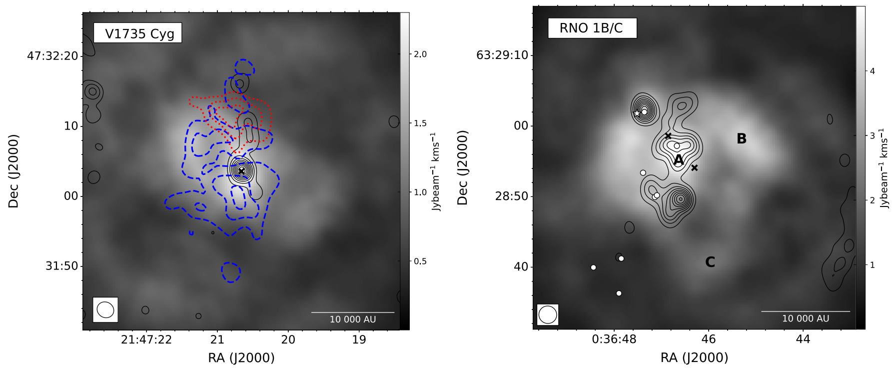

Figure 1. NOEMA CO and continuum maps of northern FUors (adapted from [7] and [8]). Left: ^{13}CO integrated intensity map of V1735 Cyg. The cross marks the optical position of the FUor, the black contours are the 2.7 mm continuum emission in units of Jy beam^{-1} at the 10...90% of the peak. The dashed contour is the blue-shifted (integrated between -0.2–2 km s^{-1}) and the dotted contour is the red-shifted lobe (integrated between 7–9.4 km s^{-1}) of the outflow at 50, 70 and 90% of their peak emission. Right: ^{13}CO integrated intensity map of RNO 1B/C. The black contours are the 2.7 mm continuum emission at the 10...90% of the peak. The two crosses are the members of the binary FUor-system (RNO 1B is at the center) and the star symbol marks an IRAS source. The letters mark clumps identified on the CO map and circles mark some of the other IR/sub-mm/mm sources in the vicinity.

these datasets to correctly detect the large-scale gas emission the interferometer would filter out.

Our maps revealed extended, fragmented gas clouds around all our targets on a few thousand au spatial scales with local peaks at or close to the FUors [7]. Some FUors like V1057 Cyg or V1735 Cyg only show one central clump, others like V1515 Cyg or V2492 Cyg are associated with several other clumps in their neighbourhood, some occasionally corresponding to other IR or radio sources if the FUor is not isolated e.g. V710 Cyg, V2493 Cyg. The central clumps which we identify as envelopes are roughly circular with radii of 1500−5000 au and with masses of 0.02−0.5 $M_\odot$. Their interior is often warmer than their surroundings with average temperatures of 20−50 K. ^{13}CO(1-0) velocity channel maps towards V1057 Cyg revealed a velocity gradient in the envelope, indicating rotation. A large scale velocity gradient was also measured in the environment of V2492 Cyg, caused by the shock front appearing as a bright Hα rim close to the star. Even outflows could be identified on some of the maps: the integrated intensities of the ^{13}CO(1-0) line wings around V1735 Cyg appear in two lobes on opposite sides of the FUor, one red-shifted, one blue-shifted (Fig. 1, left). The continuum emission of our targets is just as varied as the gas environment: some envelopes appear as strong, circular sources (e.g. V1057 Cyg, V2492 Cyg), others show many continuum features. A good example is RNO 1B/C or V710 Cas (Fig. 1, right). Clump A is located between the two members of the binary FUor-system and appears both in CO and the continuum as a strong, resolved source. Clump B is seen in CO but not in the continuum, however, the bright continuum source to the south of clump A does not appear in CO, and the other bright continuum source to the north-east appears only as a faint local CO maximum. A few of the FUors are weakly or not detected (e.g. V1515 Cyg, V733 Cep), yielding only an upper limit for the envelope mass. Maps of V582 Aur revealed that the star is located at the edge of an extended cloud structure with two well-identified velocity components, and the unresolved continuum source around the FUor is possibly a disk with a mass of 0.04 $M_\odot$ [1].

3 Future directions

Thanks to the large bandwidth and high spectral resolution of the PolyFiX correlator of NOEMA, our more recent measurements of FUor objects like RNO 127, HH 354 IRS or Gaia 17bpi cover not only the usual CO transitions with high spectral resolutions, but many other molecular species as well, providing a detailed look into the distribution of different gas tracers around the stars on interferometric scales. Synergy with ALMA continuum and CO data makes it possible to map the circumstellar vicinity from the envelope through the envelope-disk interface to the accreting disk. Due to the capabilities of the IRAM 30m backends, the single-dish maps of about 40 molecular transitions of e.g. CN, SO, HC_3N, N_2H^+ in the 3 mm band are also available for most of our targets, providing an interesting opportunity to build a multi-scale, multi-wavelength view of these diverse environments. The data allows us to examine the circumstellar morphology tracing structures of different density, physical size, and chemical history, and by utilizing chemical models, we aim to draw conclusions about the progenitors and the evolutionary path of the examined FUors. The discovery of new eruptions and the monitoring of the light curves and spectral features of already known outbursting sources will lead us to have more insight on the triggering and evolution of these intriguing events.

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