The environment around young eruptive stars

SPHERE/IRDIS polarimetric imaging of seven protostars*

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Received 9 November 2023 / Accepted 14 March 2024

ABSTRACT

Aims. Eruptive stars are a class of young stellar objects that show an abrupt increase in luminosity. These burst-like episodes are thought to dominate the stellar accretion process during the Class 0 to Class I stage. We present an overview of a survey of seven episodically accreting protostars carried out to study their potentially complex circumstellar surroundings.

Methods. The observations were performed with the instrument SPHERE, mounted at the Very Large Telescope. SPHERE is equipped with an extreme adaptive optics system that allows high-contrast imaging. We observed the eruptive stars in the $H$ band with the near-infrared imager IRDIS and used the polarimeter to extract the polarized light scattered from the stars’ surroundings.

Results. We produced polarized light images for three FUor objects, Z CMa, V960 Mon, and FU Ori, and four EXor objects, XZ Tau, UZ Tau, NY Ori, and EX Lup. We calculated the intrinsic polarization fraction for all the observed stars. In all systems we registered scattered light from around the primary star. FU Ori and V960 Mon are surrounded by complex structures, including spiral-like features. In Z CMa, we detected a point source 0.7 to the northeast of the primary. Based on the astrometric measurements from archival Keck/NIRC2 data, we find this source to be a third member of the system. Furthermore, Z CMa displays an outflow that extends for thousands of au. Unlike the other EXor objects in our sample, XZ Tau shows bright, extended scattered light structures that are also associated with an outflow on a scale of hundreds of au. The other EXors show relatively faint disk-like structures in the immediate vicinity of the coronagraph.

Conclusions. Each object shows a unique environment, but we classified the seven objects into three categories: systems with illuminated outflows, asymmetric arms, and faint disks. Asymmetric arms were only found around FUor objects, while faint disks seem to predominantly occur around EXors. Importantly, for Z CMa the detection of the faint extended structure calls into question previous interpretations of the system’s dynamic state. The streamer that was associated with a fly-by object turned out to be part of a huge outflow extending 6000 au.

Key words. instrumentation: adaptive optics – techniques: polarimetric – binaries: visual – stars: formation – stars: imaging – stars: protostars

1. Introduction

Young eruptive stars are a class of young stellar objects (YSOs) that display sudden and intense increases in luminosity, followed by a gradual decline over a period of weeks to years. The light curves and spectra of these objects exhibit a wide range of variations, making their classification a challenging task (see, e.g., Greene et al. 2008). Historical studies on the optical nebulosity around these objects underscore the ubiquity of reflection nebulae found in association with these eruptive stars at sub-parsec scales (see the review by Hartmann & Kenyon 1996).

Within the group of eruptive stars, two loosely defined categories are typically recognized and are based on the duration of the outburst and the presence of certain spectral features: FU Ori objects, often referred to as FUors, named after the class prototype, FU Orionis; and EXor objects, named after the prototype EX Lup (see Fischer et al. 2023, for a recent discussion on classification schemes). FUors have outbursts with sustained increases in bolometric luminosity, their decay timescale is about 100 years, and their spectrum is dominated by the disk viscous heating. On the other hand, EXors show spectra similar to those of T Tauri stars with high accretion. Their outbursts have amplitudes of several magnitudes, last for months, and can recur after a few years (Fischer et al. 2023). These eruptive stars are believed to go through enhanced episodic accretion (see Audard et al. 2014; Takami et al. 2019; Kóspál et al. 2021, for a review), a process that could explain the wide range of protostellar luminosities and resolve the so-called luminosity problem, which refers to the discrepancy between the observed luminosities of young, embedded low-mass protostars and the predicted luminosities from standard theoretical models (e.g., Kenyon et al. 1990). Both FUor and EXor objects undergo periodic bursts, in which material falls onto the disk from the circumstellar envelope. Therefore, resolved maps of the surroundings of these eruptive stars can help us reconstruct the accretion history of the source. These outbursts can last for months (in the case of EXors) or even decades (FUors) and are believed to be caused by a variety of mechanisms that can be investigated through high-resolution imaging, including gravitational instabilities in the disk (Armitage et al. 2001; Zhu et al. 2009), thermal instability (Bell & Lin 1994), disk fragmentation (Vorobyov & Basu 2005; Zhu et al. 2012), or interactions with a companion star or sub-stellar object (Bonnell & Bastien 1992; Lodato & Clarke 2004).

The environment around eruptive stars were studied intensively in the (sub)millimeter. Recent Atacama Large (sub)-Millimeter Array (ALMA) observations revealed complex structures in the environment around several FUor and EXor objects.
EXor objects. In the disk of V883 Ori, the water snow line was detected for the first time (Cieza et al. 2016), and the same object presents a wide outflow in the gas emission (Ruiz-Rodríguez et al. 2017a, 2022; Tobin et al. 2023). The FUor V2775 Ori shows a spectacular hourglass shape in gas emission (Zurlo et al. 2017). The object HBC 494 is surrounded by a very wide outflow (Ruiz-Rodríguez et al. 2017b) and has a resolved close companion that also hosts a compact disk (Nogueira et al. 2023). V1647 Ori shows a misaligned outflow with respect to its host nebula (Principe et al. 2018). Last but not least, the Z CMa system’s outflow was first identified by Herbig (1960), with several nebulosities associated with this active system found since then (Liimets et al. 2023).

The ALMA continuum emission of several of these sources is presented in recent works that used radiative transfer modeling to compute disk masses. For example, Cieza et al. (2018) present the analysis of the dust continuum emission and the masses of three FUors, four EXors, and the borderline object V1647 Ori. The inferred disk radii are smaller than those of T Tauri stars but have comparable disk masses, suggesting that disks around outbursting objects are more compact than those around regular stars. Hales et al. (2020) present an ALMA survey of four objects at 1.3 mm and 0′′ resolution: two FUors (V582 Aur and V900 Mon), one EXor (UZ Tau E), and one source with an unambiguous FU-EXor classification (GM Cha). From the continuum emission, they derived the masses of the dust in the disks and found that FUors are more massive than Class 0, I, and II objects of similar sizes. EXors have masses and radii comparable to those of disks around Class II objects. Kóspál et al. (2021) conducted an ALMA 1.3 mm continuum survey of ten FUors and FUor-like objects. Their findings suggest that the disks of FUors are typically a factor of 3–4 more massive and a factor of 2–5 smaller in size than Class II and Class I objects, and that a good fraction of them might be gravitationally unstable.

A compact disk might also be related to the presence of a stellar companion, as demonstrated in several studies (e.g., Long et al. 2019; Akeson et al. 2019; Zurlo et al. 2023). In general, disks observed in the (sub)millimeter around multiple stars are more compact than the ones around single stars. While a fraction of eruptive stars are in multiple systems, this might not necessarily mean that their disks have smaller sizes, because of the presence of stellar companions.

Fewer studies on the environment of eruptive stars have been carried out with adaptive-optics-assisted observations in the near-infrared (NIR). At these wavelengths, the most successful method for directly imaging the immediate surroundings of bright stars is to use a polarimeter to discern stellar light and light scattered by circumstellar material (Benisty et al. 2023). With 8 m class telescopes such as the Very Large Telescope (VLT), one can obtain resolved maps of the polarized light at separations larger than 0″1. Any polarimetric signal enclosed in the region closer in will be contained in the unresolved polarization of the central beam, which can be now measured for observations done with the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) at the VLT in Chile (van Holstein et al. 2020).

Polarimetric imaging is a potent tool for gaining a better understanding of the environment around young stars, revealing details about their composition, structure, and dynamics (see, for example, Liu et al. 2016; Avenhaus et al. 2018). It also aids in identifying disk misalignments via shadows (see, for example, Marino et al. 2015; Arce-Tord et al. 2023) and detecting magnetically aligned grains (Yang & Li 2022). For a detailed overview of scattered and polarized light observations of protoplanetary disks, we direct readers to Benisty et al. (2023) and references therein.

In the context of multiple stellar systems, polarimetric observations can additionally uncover details about the illumination pattern (Weintraub & Kastner 1993; Weber et al. 2023a). This capability enables the identification of asymmetries and complex features, shedding light on the system’s geometry and helping us discern which star is illuminating specific dust regions (Weber et al. 2023a). Such an approach enriches our comprehension of the early phases of star formation and contributes to our knowledge of the processes involved in planet formation, as well as the various conditions found in young stellar neighborhoods.

At the time of writing, there are about a hundred or so known young objects classified as eruptive stars. This number includes the ~40 objects presented in Audard et al. (2014) in a volume of 1700 pc and 80 outbursting VISTA Variables in the Via Lactea (VVV) candidates with eruptive classification confirmed spectroscopically in a volume of 10 kpc (Contreras Peña et al. 2017; Guo et al. 2021). Most of these objects are young (<1 Myr) pre-main-sequence stars and are either still heavily embedded in material from their nascent molecular cloud or parent envelope or are very distant (the case for most of the VVV sample), which hinders their observability with wavefront sensors in the optical. Pioneering work with the High Contrast Instrument for the Subaru Next Generation Adaptive Optics (HiCIAO) revealed tantalizing details of complex structures around four of these objects in the NIR (see Liu et al. 2016).

Here we present a NIR (H-band) survey of seven EXors and FUors performed with VLT/SPHERE. The SPHERE adaptive optics system operates in the optical, and thus most FUor or EXors suffer too much extinction to be observable with this instrument. The sample in this paper consists of seven well-studied examples of eruptive YSOs that are particularly amenable to observations by SPHERE. The manuscript is organized as follows: In Sect. 2 we present the observations and data reduction of the sources, in Sect. 3 we present the results and a short discussion on each individual target, and in Sect. 4 we put the main results of our survey into context. Finally, Sect. 5 summarizes our conclusions.

2. Observations and data reduction

The data presented in this manuscript are part of the survey conducted under ESO programs 098.C-0422(A) and 0100.C-0408(A) (PI: Cieza). The original SPHERE survey included all the FUors and EXors presented in Audard et al. (2014) with a R mag brighter than 13, which is the SPHERE limit for the adaptive optics: Z CMa, XZ Tau, FU Ori, V960 Mon, UZ Tau, NY Ori. EX Lup was a protected target of the SPHERE guaranteed time observations, and their data are now available in the archive under ESO program 099.C-0147(B) (PI: Beuzit). As the quality of the observations for Z CMa was such that no polarimetric cycles were completed, we added archival data from 1104.C-0415(D) (PI: Ginski).

The objects XZ Tau, UZ Tau, and NY Ori are categorized as EXors in Giannini et al. (2022), while Z CMa and V960 Mon are bona fide FUors (Cruz-Sánchez de Miera et al. 2023). The FU Ori and EX Lup systems are the prototypes of the two categories. The survey was performed with the SPHERE instrument (Beuzit et al. 2019), a high-contrast imager installed at

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1 These data are part of the ESO large program called Disk Evolution Study Through Imaging of Nearby Young Stars (DESTINYs; Ginski et al. 2020) led by C. Ginski.
the VLT and equipped with an extreme adaptive optics system (SAXO; Fusco et al. 2006; Petit et al. 2014). The NIR arm is composed of the Infrared Dual-band Imager and Spectrograph (IRDIS; Dohlen et al. 2008) and an integral field spectrograph (Claudi et al. 2008). For this study, we used the IRDIS linear-polarimetric imaging mode, to perform the polarimetric differential imaging (PDI; de Boer et al. 2020; van Holstein et al. 2020). The observations were performed in the H band, with an angular resolution of 0.05′′ and Strehl ratio of 90% for good seeing conditions (< 0.5′′). For all the observations the N_ALC_YJH_S coronagraph was implied (185 mas diameter, Guerri et al. 2011).

The observations are summarized in Table 1. The observations were performed in field-stabilized mode (all but Z CMa’s), so the contrast is not optimal for the search for companions. When observing single protoplanetary disks that exhibit a high degree of axisymmetry, it is possible to separate the signal into Qphi and Uphi components. This decomposition, coupled with the assumption of single scattering events, enables the isolation of the majority of noise within the Uphi component, with the exception of cross-talk contributions (see, e.g., Avenhaus et al. 2018). However, in the context of our observations, which encompass complex, extended signals potentially illuminated by multiple stars within the field, such decomposition cannot be performed. As an alternative, we present the rms noise of the background in the PI images as an approximation of the noise levels. It is important to note that these values are relatively high, considering that the PI images are generated by summing the squares of Q and U (see below). The rms of the background in our observations spans from 0.006 mJy arcsec$^{-2}$ to 0.1 mJy arcsec$^{-2}$ in the best case (see Fig. A.1).

Table 1. Summary of the H-band observations of the SPHERE/IRDIS survey of eruptive stars.

<table>
<thead>
<tr>
<th>Target</th>
<th>Night</th>
<th>DIT[s]</th>
<th>#frames</th>
<th>$\tau_{int}$[min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z CMa</td>
<td>2022-12-17</td>
<td>32</td>
<td>104</td>
<td>55.5</td>
</tr>
<tr>
<td>XZ Tau</td>
<td>2017-10-12</td>
<td>64</td>
<td>1</td>
<td>17.1</td>
</tr>
<tr>
<td>FU Ori</td>
<td>2017-10-12</td>
<td>24</td>
<td>24</td>
<td>9.6</td>
</tr>
<tr>
<td>V960 Mon</td>
<td>2016-12-17</td>
<td>64</td>
<td>16</td>
<td>17.1</td>
</tr>
<tr>
<td>UZ Tau</td>
<td>2017-10-27</td>
<td>64</td>
<td>14</td>
<td>14.9</td>
</tr>
<tr>
<td>NY Ori</td>
<td>2016-12-16</td>
<td>32</td>
<td>24</td>
<td>12.8</td>
</tr>
<tr>
<td>EX Lup</td>
<td>2017-05-16</td>
<td>64</td>
<td>22</td>
<td>23.5</td>
</tr>
</tbody>
</table>

Notes. DIT gives the detector integration time per frame, #frames is the number of frames, and $\tau_{int}$ is the total on-target integration time. (1)From the DESTINYS survey (PI: Ginski). (2)From the SPHERE GTO survey (PI: Beuzit).

In addition, IRDAP computes images of $Q_\phi$ and $U_\phi$ (Schmid et al. 2006) using the definitions of de Boer et al. (2020). The $Q_\phi$ image is typically preferred for displaying circumstellar environments in polarized light as it has lower noise in comparison to $PI$. However, in the presence of multiple light sources, the interpretation of the $Q_\phi$ and $U_\phi$ images is nontrivial (Weber et al. 2023b). We used the PI image for Z CMa, XZ Tau, FU Ori, and V960 Mon because for these objects there are multiple light sources and the circumstellar disks are bright. On the other hand, for UZ Tau, NY Ori, and EX Lup we used the $Q_\phi$ image because the circumstellar material around those objects is faint and there is only a single, central light source.

To reduce the presence of Poisson-noise in our images, we further made use of the denoise package, which is based on the particle smoothing kernel described within the context of the visualization tool SPLASH (Price 2007). The denoising procedure is most efficient when directly applied to the $Q$ and $U$ products before combining them to $PI$ or $Q_\phi$. It has to be applied with care, however, in regions where $Q$ and $U$ change strongly over small spatial scales, as the smoothing can lead to artificial cancellation of polarization. This is typically the case in the bright regions close to the image center. We, therefore, applied a moderate smoothing kernel (-beam=1.6)$\theta$ and refrained from modifying the bright areas (where the signal-to-noise is high anyway) by setting an individually selected maximum value (-imax) for the procedure.

3. Results

In the following sections, each object that is part of this survey is presented individually. We summarize the data present in the literature for each individual target and the new results derived from the SPHERE observations. A general discussion follows the dedicated sections for each target.

3.1. Z CMa

Z Canis Majoris is a young binary star composed of an FU Ori-like object, the southeastern component (e.g., Szabó et al. 2023), and an EXor object, the northern star (van den Ancker et al. 2004; Bonnefoy et al. 2017), which is also a Herbig Be star. The two stars, separated by 0.7″, were resolved via high-contrast imaging several times in the past (see, e.g., Hinkle et al. 2013; Canovas et al. 2015; Antonucci et al. 2016; Bonnefoy et al. 2017; Takami et al. 2018). Antonucci et al. (2016) presented detection of both companions, which prevents the association of the extended features around the binary star with one particular star. For the distance we assumed the value proposed in Dong et al. (2022) of 1125 ± 30 pc, obtained by calculating the Gaia Early Data Release 3 distance to 62 young members of CMa R1.

2 From the SPHERE manual.

3 https://github.com/danieljprice/denoise
Scattered light images revealed a large disk around the system, extending 1500 au (Liu et al. 2016). In the millimeter, on the other hand, ALMA detected compact emission (~20 au) around each of the two components (Dong et al. 2022). But the most interesting feature, revealed in both the NIR and millimeter is the enormous streamer toward the southwest, as shown in Fig. 1 and 2. One scenario proposed to explain the origin of this streamer is the encounter with a fly-by object (Dong et al. 2022). Hydrodynamical simulations of a fly-by object interacting with the material around the two stars and subsequent radiative transfer showed that such an event can reproduce the observations of the streamer. Moreover, an unresolved compact source emission in the ALMA images is consistent with being the perturber fly-by. This putative perturber is not detected in the NIR. The fact that the object is not detected in the SPHERE images means that its mass is below our detection limits. If the radio signal is real ($S/N \sim 27$), the object would be most probably substellar or a distant background object. Deeper and more sensitive observations are needed to confirm its nature.

The final Z CMa image is shown in Fig. 1. The polarized light image shows several faint structures that were never detected before. The most spectacular structure is an arch-shaped filament that seemingly connects the streamer, extends for thousands of au, and ends on the central star. This detection suggests that the streamer is in reality a portion of an outflow that is brighter due to forward scattering. Opposing this arch, we also find a dim contribution east of the star, which appears to be sub-structured, potentially shaped by shock-waves connected to the outburst event. The SPHERE image further reveals light reflected from the near side of the outflow, northwest of the central star.

Another point source is detected to the northeast of the central star, also showing emission in the 1.3 mm image (see Fig. 2). To investigate the nature of this object, we reduced Keck/NIRC2 archival data of the system. The NIRC2 image was obtained on 2017-1-11 in the $L^\prime$ filter, employing the vortex coronagraph. The final angular differential imaging (ADI; Marois et al. 2006) reduced image is shown in Fig. 3. The quality of the data is poorer than the SPHERE images due to the low rotation angle of 11 degrees, so the image was used with the purpose of re-detecting the point source.

To check if the point source (object 2 in Fig. 3) is comoving with the system, we measured the astrometric positions in the two epochs separated by 5 years. In the SPHERE data we measured its position with respect to the central star to be $\Delta RA = 549 \pm 3$ mas and $\Delta Dec = 555 \pm 3$ mas with the same method presented in Zurlo et al. (2016). In the NIRC2 image the measured position is $\Delta RA = 549 \pm 15$ mas and $\Delta Dec = 558 \pm 15$, the error bars include the standard deviation of the results of three different centering methods and the true north error. Given the proper motions of the star (in 5 years it moves $\Delta RA = -24$ mas and $\Delta Dec = 19$), the object is indeed very likely part of the system, which makes Z CMa a triple system and not a binary. The contrast of the star is $\Delta H = 11.2$ and $\Delta L = 10.3$ mag with respect to the star behind the coronagraph (northern component).

### 3.2. XZ Tau

XZ Tau is a known binary system (e.g., Dodin et al. 2016), composed of an M1.5 spectral type star and a less massive (M3/M3.5) southern companion (White & Ghez 2001). The distance to the system is 146 pc, assuming it is part of the L1551 region (Roccatagliata et al. 2020). Both components of XZ Tau are spectroscopically cataloged as EXors in Coffey et al. (2004) and Giannini et al. (2022), according to whom the evolution of the outburst is compatible with that of EXor stars.

XZ Tau was identified with a bipolar collimated outflow in Mundt et al. (1990) and later spatially resolved with the *Hubble* Space Telescope (HST) in Krist et al. (1997). A multi-epoch HST study of the XZ Tau binary using $R$-band, H-alpha, and [S II] emission between 1995 and 2005 shows this outflow is complex and expanding (Krist et al. 2008). The northern outflow appears as a succession of bubbles and a faint southern counter-bubble was identified with HST data in 2004. As discussed in more detail in Krist et al. (2008), while both XZ Tau A and B have stellar jets, the bubble and counter-bubble appear aligned with the jet from XZ Tau A. This morphologically complex feature can be explained as previously ejected material interacting with the jet component of XZ Tau A. In 2005, the length of the northern XZ Tau bubble extended ~6 arcseconds from the binary midpoint. ALMA imaging of this source confirms that the bubble features align with the XZ Tau A component (Zapata et al. 2015).

The system was observed with ALMA several times, in Cycles 2, 4, and 5 (Ichikawa et al. 2021). In the ALMA dust continuum emission the two components of the system, XZ Tau A (in the southeast) and XZ Tau B (in the northwest) show two circumstellar disks. Both of them are unresolved even in the highest resolution configuration (0.03'). Ichikawa et al. (2021) estimated disk masses of $(0.77 \pm 0.37) \times 10^{-3} M_\odot$ for A and $(0.96 \pm 0.36) \times 10^{-3} M_\odot$ for B. Combining the ALMA astrometry from the three Cycles and the NIR observations presented in Dodin et al. (2016), the best orbital fitting indicates a noncircular orbit of the two components of XZ Tau. Finally, Ichikawa et al. (2021) found that not only the two circumstellar disks are misaligned to each other, but also to the orbital plane of the binary system. They suggest that this is an indication that turbulent fragmentation played a major role in the formation of this young binary system.

In the IRDIS FoV, the binary is resolved, and no other object is detected. An outflow is seen toward the northeastern part of the system. This faint structure was not observed before and has no counterpart in the ALMA data. The feature seems to be connected with the lower-mass A component. The outflow extends for several arcseconds, toward the northeast of the system. Diffuse signal is recovered in a cone shape with the axis pointing toward the northeast of the system. On the opposite side, very faint emission also suggests that we are seeing the southern outflow of the YSO. Indeed, in the same regions, gas emission is detected in the $^{13}$CO channel map (Ichikawa et al. 2021).

#### 3.3. FU Ori

The star FU Orionis is the archetype of the FUor eruptive objects. For this reason, it was extensively studied in the past. It is located at a distance of 408 ± 3 pc (Gaia Data Release 3; Bailier-Jones et al. 2021) and has a mass of $0.3 M_\odot$ (Beck & Aspin 2012). The age of the system is estimated to be ~2 Myr (Beck & Aspin 2012). FU Ori is part of a wide binary system, its companion FU Ori S, probably a 1.2 $M_\odot$ pre-main-sequence K star, is located at a separation of ~0.5 away and position angle of 161 degrees (Wang et al. 2004; Beck & Aspin 2012). FU Ori started its outburst in 1936 (Wachmann 1954; Herbig 1966).

The surroundings of both stars in the binary system present various features: using Subaru/HiCIAO NIR imaging, Liu et al. (2016) detected a bright arm, or arch-shaped feature, east of the primary star. The same finding was presented in Takami et al.
Fig. 1. Gallery of all the SPHERE polarized light images of the eruptive stars in the $H$ band. North is up, and east is to the left. The black circle indicates the region masked by the coronagraph. The color scale was optimized for a better visualization; in Fig. A.1 a color bar indicates the values of the surface brightness.
Z CMa
1000 au

Fig. 2. IRDIS image of Z CMa with the ALMA 1.3 mm continuum contours from Dong et al. (2022) overplotted in white. The stellar companion is detected in the ALMA image, and the object in the southwest of the star (labeled emission “C” in Dong et al. 2022) has no NIR counterpart.

Fig. 3. ADI image of Z CMa taken with Keck/NIRC2. The streamer is visible and marked as feature 1. A point source is also detected (feature 2), and a faint emission is present in the southeast of the star (feature 3). For completeness, we show in Fig. 1 the SPHERE image of the system.

3.5. UZ Tau

The system of UZ Tau is a quadruple, composed of a spectroscopic binary, UZ Tau E, with a separation of ~0.03 au (Mathieu et al. 1996) and surrounded by a large circumbinary disk (Tripathi et al. 2018), and an M3+M3 binary pair with a 48 au projected separation, UZ Tau W. UZ Tau E is located at a distance of 123 ± 7 pc (Gaia Collaboration 2023), the renormalized unit weight error value is high (15.3). The EXor object is the spectroscopic binary UZ Tau E, which shows moderate short-term variability typical of the EXor objects (Herbig 1977; Lorenzetti et al. 2007). Its variability could be explained by the interaction between the spectroscopic binary and the disk, as suggested in Jensen et al. (2007).

UZ Tau E was observed with ALMA by Long et al. (2018) and Hales et al. (2020). Long et al. (2018) observed the source with a 0.′′13 × 0.′′11 resolution, and they reported an inner cavity and two emission bumps. They found three rings at 11, 17, and 77 au from the central stars. From the 13CO and C18O emission, Czekala et al. (2019) determined that the circumstellar disk is almost coplanar with the orbit of the spectroscopic binary, Hales et al. (2020) observed again the system with a lower resolution and derived the mass of the disk (22 M_Jup), the inclination (59 deg), the major and minor axes (668 and 396 mas, respectively). The disk shows a clear Keplerian pattern of a Class II disk. This might be an indication that the EXor objects are in a more evolved stage than FUors.

The reduced IRDIS image is shown in Fig. 1. An inclined disk is detected around UZ Tau E, even if the emission is faint. No substructure is seen in the NIR. No extended emission around the system is detected in the IRDIS image. A larger FoV is also shown in Fig. 4 and presented in Sect. 4.4, where the visual binary system UZ Tau W is detected.
3.6. NY Ori

NY Ori, also known as Parenago 2199, is a young eruptive star located at a distance of 403 \( \pm \) 5 pc (Gaia Collaboration 2021) in the Orion Nebula Cloud complex, more specifically in the Orion A sub-cloud (Zari et al. 2019). In Giannini et al. (2022) it is listed as a single system, even if it is visually close to the star V566 Ori (also called Parenago 2118), located at 5.5 arcsec from NY Ori, and a distance of 388 \( \pm \) 3 pc (Gaia Collaboration 2020). This close star polluted many light curves of the EXor object in the past (see, e.g., Jurdana-Šepić et al. 2017). NY Ori was part of the ALMA FUor-EXor survey presented in Cieza et al. (2018). They found that the continuum emission shows a single disk, spatially resolved, with a mass of \( 40^{+10}_{-10} \) M\(_{\text{Jup}} \) and radius \( 76^{+5}_{-7} \) au inferred for the radiative transfer modeling, which assumes a gas-to-dust ratio of 100. The disk is also detected in the gas lines \(^{13}\text{CO} \) and C\(^{18}\text{O}\), as a compact emission. There is no evidence of outflows from the \(^{12}\text{CO} \) emission. Jurdana-Šepić et al. (2017) reported that no significant outburst (with a duration longer than 6 months) occurred during monitoring of 40 yr (since 1961). On the other hand, Lorenzetti et al. (2016) reported on a rapid brightness variability monitored from 2011 to 2015 in a very short cadence (e.g., a fading of 1.4 mag in 2 days). The monitoring was part of the EXORCISM program (EXOR Opti-cal and Infrared Systematic Monitoring, Antoniucci et al. 2013; Lorenzetti et al. 2009).

There are no other high-contrast visible/NIR data in the ESO or Keck archives besides the SPHERE data presented in this work. In the IRDIS image, the signal around the EXor is very low, but a faint disk is seen around the star. The reduced image is shown in Fig. 1. The close star V566 Ori is easily visible in the NW of NY Ori, as shown in Fig. 4. The astrometrical positions are: \( \Delta RA = 3^{h}280 \pm 0^{m}006 \), \( \Delta Dec = 4^{d}711 \pm 0^{m}004 \) with respect to the central star.

3.7. EX Lup

EX Lup is the prototype of the EXor objects (see, e.g., Sipos et al. 2009; Aspin et al. 2010). The IRDIS/SPHERE data are extensively presented in Rigliaco et al. (2020). We include the final image in Fig. 1 for completeness of the sample. The detection of the close environment around EX Lup is very similar to the one around NY Ori.

4. Discussion

4.1. Taxonomy of eruptive stars

Despite the small number of eruptive stars that are observable in polarized light, it is still possible to discern between three types of structures that are found around FUors and EXors: objects with outflows, asymmetric arms, and faint disks. The structures seen in these systems span a huge range of spatial scales as it can be visualized in the up-to-scale Fig. 5.

In the first category are Z CMa and XZ Tau. In both cases, only one side of the putative outflow is bright enough to be well detected in the SPHERE images. This is probably due to an illumination effect and tells us that the part of the outflow visible in polarized light is the near side of the hourglass. The distances to these two objects differ by an order of magnitude. Consequently, the outflow seen in the southern part of Z CMa extends for \( \sim 6000 \) au, making it more than 10 times bigger than the outflow on the northern side of XZ Tau. In this context, it is important to note that Z CMa is an FUor object, while XZ Tau is an EXor.

FU Ori and V960 Mon, both FUor objects, show complex asymmetric features. For these two objects, the onset of their current outburst was recorded, in 1936 and 2014, respectively. FU Ori shows a bright arm, arch-shaped features, and a faint tail toward the east. The structure of the environment around FU Ori makes it unique, with no similar object among the other YSOs. V960 Mon is surrounded by huge spiral arms, extending for thousands of au, both in the south and in the north. V960 Mon and Z CMa show the most extended structures of the sample.

For UZ Tau, NY Ori, and EX Lup, all classified as EXors, the signal is similar to that expected from self-shadowed disks (see, e.g., Garufi et al. 2022). UZ Tau is surrounded by an inclined and faint disk, NY Ori is only marginally resolved and shows an asymmetry in the southwest. Very similarly, EX Lup also has an
inclined disk, very faint and compact. In summary, among the EXors of the survey, only XZ Tau shows a prominent feature, while the others show mostly axisymmetric faint disks.

There is no obvious reason why an inclined disk should be faint in scattered light. Quite the opposite, on average they appear brighter because of smaller angles of scattering, providing an increased number of photons, and are probed (Garufi et al. 2022). Therefore, the faintness of the disks in question must be intrinsic to the system.

It is important to note that the three FUors are presently all in the range $L_{\text{bol}}$ of hundreds of $L_\odot$; the EXors are a few tenths to a few $L_\odot$ (see Table 1 in Audard et al. 2014). This luminosity dichotomy can explain the different illumination of the extended features that we see around the eruptive stars and their luminosities.

### 4.2. Polarization analysis

The polarization of light observed from an object or area can be described by its degree of linear polarization (DoLP) and the angle of linear polarization (AoLP). Those two quantities give the polarization fraction and direction and are related to the Stokes components:

\[
\text{DoLP} = \frac{P_I}{I},
\]

\[
\text{AoLP} = \frac{1}{2} \arctan \left( \frac{U}{Q} \right),
\]

where $I$ is the total intensity.

For bright objects, locally dominating the total intensity, one can calculate both the DoLP and AoLP. Therefore, we quantified the polarization contained within the signal of all distinguishable stars in our observational dataset. The corresponding values are listed in Table 2. It is important to note that the commonly used term “stellar polarization” can be somewhat misleading, as the observed polarization of a star does not represent an inherent quality of its emitted light, but rather arises from unresolved scattering within the point-spread function of the telescope. This scattering can originate from dust grains close enough to the star to not be discernible, or it may be influenced by scattering events along the line of sight, potentially involving interstellar dust particles (see van Holstein et al. 2021, for a discussion). For the systems that do not show significant scattering in the region of the residuals of the adaptive optics (UZ Tau, NY Ori, and EX Lup), we measured the central star’s polarization from a mask over this area, as directly provided by the IRDAP pipeline. For the other systems and the off-centered companions, we measured the polarization directly from an aperture of 8 pixels centered on the star. For the measurement, we rejected the pixels that are closer than 0.05 to the star to avoid including saturated pixels. The values’ systematic variability when varying the shape and size of this mask is expected to dominate the error of the measurements.

#### Table 2. Stellar polarizations expressed by the degree of linear polarization (DoLP) and angle of linear polarization (AoLP).

<table>
<thead>
<tr>
<th>Object</th>
<th>DoLP</th>
<th>AoLP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z CMa</td>
<td>0.3%</td>
<td>70°</td>
</tr>
<tr>
<td>Z CMa ‘D’</td>
<td>1.1%</td>
<td>85°</td>
</tr>
<tr>
<td>XZ Tau A</td>
<td>2.6%</td>
<td>31°</td>
</tr>
<tr>
<td>XZ Tau B</td>
<td>3.1%</td>
<td>154°</td>
</tr>
<tr>
<td>FU Ori N</td>
<td>0.3%</td>
<td>86°</td>
</tr>
<tr>
<td>FU Ori S</td>
<td>0.4%</td>
<td>128°</td>
</tr>
<tr>
<td>V960 Mon A</td>
<td>1.7%</td>
<td>107°</td>
</tr>
<tr>
<td>V960 Mon B</td>
<td>0.2%</td>
<td>142°</td>
</tr>
<tr>
<td>UZ Tau E</td>
<td>0.7%</td>
<td>2°</td>
</tr>
<tr>
<td>UZ Tau Wn</td>
<td>0.5%</td>
<td>37°</td>
</tr>
<tr>
<td>UZ Tau Ws</td>
<td>0.3%</td>
<td>48°</td>
</tr>
<tr>
<td>NY Ori</td>
<td>0.4%</td>
<td>33°</td>
</tr>
<tr>
<td>Parenago 2118 (1)</td>
<td>0.4%</td>
<td>118°</td>
</tr>
<tr>
<td>EX Lup</td>
<td>0.5%</td>
<td>168°</td>
</tr>
</tbody>
</table>

**Notes.** (1)Parenago 2118 was measured from the FoV around NY Ori.

---

**Fig. 5.** SPHERE polarized light images of the eruptive stars at the same projected spatial scale. The bar marking 500 au is shown in the bottom-right corner and applies for all seven subset images.
For circumstellar scattering regions, it is often impractical to determine the DoLP when the total intensity is predominantly influenced by the stars themselves, while the polarized intensity is a result of light scattering off circumstellar material. Consequently, our analysis is confined to the measurement of the AoLP. Figure 6 presents an adapted version of the polarized light gallery from Fig. 1, with an emphasis on the superimposed polarization vectors that represent the local AoLP. Under conditions involving a single light source and singular scattering events, these vectors are anticipated to align orthogonally to the direction of incoming light. As shown in Fig. 6, the observed vector patterns suggest illumination predominantly by the central star. However, for NY Ori and EX Lup, definitive conclusions are challenged by the low signal-to-noise ratio in the data.

4.3. Reinterpretation of Z CMa’s streamer

Our observations reveal a significant connection between the streamer in Z CMa and an extensively illuminated large-scale outflow-like structure that was previously undetected. The consistent opening angles between the streamer and the illuminated outflow suggest the need for a reevaluation of the recently proposed tidal tail interpretation (Dong et al. 2022).

It is worth noting that the millimeter emission at the end of the tail (a proposed stellar flyby, marked as “C” in their Fig. 1; Dong et al. 2022) does not correspond to any visible counterpart in either the total intensity or polarized intensity images of the SPHERE observation as in Fig. 2. Furthermore, recent findings related to possible gravitational instability clumps around the erupting object V960 Mon provide valuable evidence for clumps...
of millimeter emission found at intermediate distances around eruptive stars (Weber et al. 2023b). Future ALMA observations of the source may shed light on the nature of the emission, which might be an ejected remnant, possibly linked to the clumps that triggered Z CMa’s eruptive behavior.

Nevertheless, the exceptional collimation exhibited by the streamer-like feature on one side of the extended outflow, as seen in polarized light, coupled with its distinctive hook-like morphology at its tip, poses a challenge to a typical outflow model. One possibility could be that the ALMA “C” source identified as a flyby object may not have directly perturbed the circumstellar disk but, instead, may have perturbed the large-scale outflow, resulting in the collimation of material to form the observed elongated filament. Investigating this idea through hydrodynamic flyby simulations, while considering the influence of the primary star’s envelope and outflow, could offer valuable insights into the collimation of material and its connection to dynamical effects, where a massive object in motion leaves behind a collimated wake.

4.4. Multiplicity

Among the stars in our sample, five out of seven systems are multiple. Most probably NY Ori and EX Lup are the only single stars, even if Parenago 2118, the star located to the northwest of NY Ori share a similar parallax (see Fig. 4). In the case of EX Lup, the data presented here exclude the presence of a visual binary, and Bailey (1998) excluded a spectroscopic companion. On the other hand, Rigliaco et al. (2020) proposed that the one-sided polarized light signal around EX Lup could be due to shadowing by a moderately misaligned inner disk. In a general study, Nealon et al. (2019) showed that the physical origin of this misalignment can be due to a massive planet on an inclined orbit. In general, observations of young circumstellar disks demonstrated that gas and dust surrounding YSOs can be heavily affected by multiplicity (see, e.g., Akeson & Jensen 2014; Akeson et al. 2019; Zurlo et al. 2020, 2021, 2023; Offner et al. 2023, and references therein).

The fact that multiplicity can be related to eruptive stars was suggested in the past (see, e.g., Bonnell & Bastien 1992). Reipurth & Aspin (2004) suggested that the decay of a binary system due to the interaction of the companion with the circumbinary disk can cause disk instability. With the exception of the two objects mentioned above, the systems presented in this survey are all visual multiples: Z CMa has two stellar companions at ~100 and ~800 au separation (detected in our data for the first time), XZ Tau at ~30 au, FU Ori at 200 au, V960 Mon at 400 au, and UZ Tau is a quadruple system. We note that, even if it seems that most eruptive objects have companions, the majority of these multiple systems are widely separated. As pointed out by Audard et al. (2014), if binarity was the main trigger of the outburst, it would happen preferably in close binary systems (i.e., less than 10 au). Apart from UZ Tau, which is a spectroscopic binary, this is not known to be the case for all the other systems. To confirm or discard this mechanism as the origin of eruptive stars high-resolution or spectroscopic observations are needed to probe the stars’ vicinity. In particular, a high-contrast imaging campaign to look for giant companions around the stars would help in understanding if substellar close companions are responsible for the outbursts, as suggested in Lodato & Clarke (2004).

5. Conclusions

In this paper we report on a survey of seven eruptive stars observed in polarized light with the instrument SPHERE/IRDIS.

The objective of the survey was to observe all the episodically accreting objects observable with SPHERE, whose adaptive optics system is limited by the magnitude of the central star in the visible. Given the young age of these kinds of objects, most of them are embedded and therefore faint in the visible. The survey observed Z CMa, XZ Tau, FU Ori, V960 Mon, UZ Tau, NY Ori, and EX Lup. Three objects are FUor-like sources (Z CMa, FU Ori, and V960 Mon), and the rest are EXors. All the objects show polarized signals in the IRDIS images.

Our observations of eruptive stars in polarized light reveal three main structures: outflows, asymmetric arms, and faint disks. Notably, Z CMa and XZ Tau represent the outflow category, with Z CMa’s extensive outflow surpassing XZ Tau’s. It is worth noting that Z CMa is an FUor-like object, while XZ Tau is an EXor. FU Ori and V960 Mon, both FUor objects, exhibit distinct features, while UZ Tau, NY Ori, and EX Lup, identified as EXors, display a faint disk-like signal, with XZ Tau standing out for its prominent feature. Being younger and far more luminous, the FUors drive and illuminate outflows, whereas the EXors no longer drive outflows (at least not extensive FUor-like outflows) and would be incapable of illuminating the outflow walls or cavities to the same extent as the FUors.

The unprecedented quality of the polarized light image for Z CMa revealed faint large-scale structures that seem to be connected to a previously detected, bright filament. This challenges the interpretation of this filament as a fly-by feature and suggests its connection to a past outflow event.

Of the stars observed, all are multiple systems except NY Ori and EX Lup. Evidence indicates that the interaction of companions with the circumstellar disk could lead to disk instability, possibly triggering the outburst in eruptive stars. In fact, the systems surveyed here have various separations, and the presence of widely separated companions might not be the primary trigger for the outbursts. However, further high-resolution observations, especially high-contrast imaging campaigns in pupil-tracking mode, are needed to investigate the role of giant or substellar close companions in the eruption mechanisms of these stars. For example, the possibility of a substellar companion shaping the disk around EX Lup was proposed in the past. SPHERE, once again, is a good instrument to perform this kind of observation, along with GPI, SCExAO, or JWST.

Acknowledgements. We thank the two referees for their comments that substantially improved the manuscript. We are thankful to R. Dong for the fruitful discussions and for providing the ALMA data on Z CMa. The authors acknowledge support from ANID – Millennium Science Initiative Program – Center Code NPN2021_080. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. P.W. acknowledges support from Fondecyt grant 3220399. S.P. acknowledges support from Fondecyt Regular grant 1231663.

References


Appendix A: Gallery in flux units

We present in this appendix the same gallery of Fig.1 with a fixed color bar for all the objects. Each color indicates the surface brightness in mJy/arcsec$^2$.

Fig. A.1. SPHERE polarized light images of the eruptive stars. The color bar applies to all the images and helps the reader retrieve the surface brightness of the features around the stars.