Time-variable Jet Ejections from RW Aur A, RY Tau, and DG Tau*

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Abstract

We present Gemini-NIFS, Very Large Telescope-SINFONI, and Keck-OSIRIS observations of near-IR [Fe II] emission that are associated with well-studied jets from three active T Tauri stars—RW Aur A, RY Tau, and DG Tau—taken from 2012 to 2021. We primarily cover the redshifted jet from RW Aur A and the blueshifted jets from RY Tau and DG Tau, in order to investigate long-term time variabilities that are potentially related to the activities of mass accretion and/or the stellar magnetic fields. All of these jets consist of several moving knots, with tangential velocities of 70–240 km s−1, which were ejected from the star with different velocities and at irregular time intervals. Via comparisons with the literature, we identify significant differences in the tangential velocities between 1985–2008 and 2008–2021 for the DG Tau jet. The sizes of the individual knots appear to increase with time, and, in turn, their peak brightnesses in the 1.644 μm emission decreased by up to a factor of ~30 during the epochs of our observations. The variety of decay timescales measured in the [Fe II] 1.644 μm emission could be attributed to different pre shock conditions should the moving knots be unresolved shocks. However, our data do not exclude the possibility that these knots are due to nonuniform velocity/density/temperature distributions with another heating mechanism, or, in some cases, due to stationary shocks without proper motions. Spatially resolved observations of these knots with significantly higher angular resolutions will be necessary to better understand their physical nature.

Unified Astronomy Thesaurus concepts: Stellar jets (1607); T Tauri stars (1681)

1. Introduction

Young stellar objects (YSOs) of various masses and at various evolutionary stages are known to host collimated jets. Many of them, in particular those associated with Class I–II YSOs, are known to be associated with atomic and ionic emission lines at optical and IR wavelengths. Jets from some young systems (Class 0–I) are associated with molecular line emission, in particular near-IR (NIR) H2 and millimeter SiO/CO emission, while these lines are faint or absent in the more evolved phase (Class II or pre-main-sequence). Furthermore, X-ray and/or centimeter continuum emissions have been observed toward some jets. See Ray et al. (2007) and Frank et al. (2014) for reviews of these observations.

Theoretical work over previous decades has predicted that the jets play an essential role in protostellar evolution, removing excess angular momentum from accreting material and allowing mass accretion to occur (e.g., Blandford & Payne 1982; Pudritz & Norman 1983; Pudritz 2000; Shu et al. 2000; Königl & Bai 2016). This scenario has been supported by a statistical correlation between the observed mass ejection and accretion rates for many pre-main-sequence stars (e.g., Cabrit et al. 1990; Hartigan et al. 1995; Calvet 1997), and by observations of spinning motions in the jet (e.g., Bacciotti et al. 2002; Coffey et al. 2004, 2007; Lee et al. 2017).

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Understanding the jet-driving mechanism and the detailed physical link between it and protostellar evolution are two of the most important issues for star formation theories.

Several theories have been proposed for jet launching and driving, as well as the physical link with mass accretion. There are two main theories for popular magnetocentrifugal wind models: (1) X-wind (Shu et al. 2000), in which the jet launches from the inner edge of the disk ($r \leq 0.1$ au); and (2) disk wind (Königl & Pudritz 2000), in which the jet-launching region covers a larger portion of the disk surface on a scale of a few astronomical units. Alternative mechanisms for jet driving include magnetic pressure (e.g., Machida et al. 2008) and the reconnection of magnetic fields between the star and the disk (reconnection wind; see, e.g., Bouvier et al. 2014 for a review). However, observational studies of the above theories have been hampered by the limited angular resolution of present telescopes (typically as good as $\sim 0.1''$; $\sim$10 au in the nearest star-forming regions; see Frank et al. 2014 for a review).

Therefore, we have relied on observations of relatively extended parts ($\gtrsim$10 au from the star) of the jet to tackle the above issue. Some researchers have observed spinning motions, and shown that these are consistent with the predictions of magnetocentrifugal wind models, such as the X-wind and disk wind models (e.g., Bacciotti et al. 2002; Coffey et al. 2004; Lee et al. 2017). Garufi et al. (2019) and Takami et al. (2020) have reported a possible time correlation between jet knot ejections from active pre-main-sequence stars and their potential signatures of mass accretion, such as optical photometry and spectroscopy. The measurements of Takami et al. (2020) suggest that each jet knot ejection occurs within $\sim$100 days of an enhancement of mass accretion. Such a short delay timescale would be explained by the jet launching occurring within 0.1 au of the star.

Most of these studies are based on observations of jets for a single epoch or two, despite the timescale of their evolution being millions of years (Stahler & Palla 2004). Although multi-epoch observations that are executable by human beings are significantly shorter than the latter, long-term ($\gtrsim$1 yr) monitoring observations of the jet are still useful for investigating the stability of their physical conditions, in order to study the evolutions of protostars and young stars. The time variabilities of the jet ejections from pre-main-sequence stars are much less well known than those from optical photometry and spectra, some of which are probably due to time-variable mass accretion (see Bouvier et al. 2007, 2014 for reviews). On the other hand, we can observe the jets from pre-main-sequence stars that were ejected even hundreds of years ago (e.g., Berdnikov et al. 2017). In this context, detailed studies of these jets are potentially useful for investigating the time variations of mass accretion and/or stellar activities over significantly longer timescales than the entire history of spectroscopic observations of pre-main-sequence stars to date.

In this paper, we present long-term monitoring data for the jets that are associated with three of the best-studied pre-main-sequence stars: RW Aur A, RY Tau, and DG Tau. We have monitored their jet ejections from 2012 to 2021 in [Fe II] 1.644 $\mu$m emission, the brightest emission line in the NIR, using the technique of integral field spectroscopy with adaptive optics (AO). The rest of this paper is organized as follows. In Section 2, we summarize the understanding of these jets and their host stars to date. In Section 3, we describe the observations and data reduction. In Section 4, we present the results and analyze them, tentatively attributing the observed jet knots to “moving knots,” as in many previous studies. In Section 5, we summarize time-variable jet ejections, including comparisons with the literature, and discuss the physical nature of the knotty structures that we have observed. We offer a summary and conclusions in Section 6.

### 2. Targets

In Table 1, we summarize the main properties of the target stars. In Sections 2.1–2.3, we summarize our understanding of the individual target jets and their host stars to date.

#### 2.1. RW Aur A

RW Aur A is associated with a brighter redshifted jet and a fainter blueshifted jet, extending over a few arcminute scale in opposite directions (Hirth et al. 1994, 1997; Bacciotti et al. 1996; Mundt & Eislöffel 1998; Berdnikov et al. 2017). The asymmetry in the jet emission is either due to different mass ejection rates between the redshifted and blueshifted jets (Liu & Shang 2012) or to the different physical conditions of the surrounding gas on the two sides, with similar mass ejection rates (Melnikov et al. 2009).

The observed jets consist of 3–9 knots within 15″ of the star. These have been extensively observed at high angular resolutions ($\sim0.1''$) at optical ([O I] 6300/6363 Å, [S II] 6713/6716 Å, and [N II] 6583 Å—Doughados et al. 2000; Woitas et al. 2002; Lopez-Martin et al. 2003; Coffey et al. 2008) and NIR wavelengths ([Fe II] and H$_2$ mainly, with the brightest lines at 1.644 $\mu$m and 2.122 $\mu$m, respectively—Pyo et al. 2006; Beck et al. 2008; Hartigan & Hillenbrand 2009; Takami et al. 2020), using the Space Telescope Imaging Spectrograph (STIS) on board the Hubble Space Telescope...
X-ray observations by Skinner & Güdel (2014) have shown that the redshifted jet, at least, appears to be associated with X-ray emission. The authors point out that the shock velocities inferred from optical and NIR observations are too low to explain this emission, suggesting the presence of another heating mechanism, e.g., via energy transfer from the star through the internal magnetic field in the jet.

A number of optical and NIR spectroscopic observations have been made in order to understand magnetospheric accretion and wind activities close to the star (e.g., Petrov et al. 2001a; Alencar et al. 2005; Facchini et al. 2016; Takami et al. 2016; Lisse et al. 2022). The star appears to have been photometrically stable over many years (e.g., Beck & Simon 2001; Grankin et al. 2007), but it has shown peculiar photometric changes at a variety of wavelengths since 2010 ($\Delta m_{\nu}$ $\sim$ 3 mag, $\Delta m_K$ $\sim$ 2 mag; e.g., Rodriguez et al. 2013, 2018; Petrov et al. 2015; Schneider et al. 2015; Shenavrin et al. 2015; Bozhinova et al. 2016; Lamzin et al. 2017; Gunther et al. 2018; Dodin et al. 2019). Many of these authors have attributed the photometric variations to occultations by dusty layers or blobs that are associated with the inner disk region or a wind. This explanation is corroborated by the polarimetric observations of Dodin et al. (2019), which show a larger polarization in the faint state, indicating a larger contribution of scattered light to the observed brightnesses. See also Koutoulaki et al. (2019) for the same interpretation, with NIR spectral variability.

Takami et al. (2016) and Takami et al. (2020) have observed different optical line profile variabilities between the bright and faint states, and discussed the possibility of the photometric variabilities being associated with mass accretion. Some line profiles show larger or more complicated time variations in bright states, which can be attributed to the occurrence of magnetohydrodynamical (MHD) instabilities of accretion flows at high mass accretion rates (Romanova et al. 2008; Kurosawa & Romanova 2013). Takami et al. (2020) have reported a possible correlation between these variabilities and jet knot ejections. Remarkable optical line profile changes have also been observed by Petrov et al. (2001a), Petrov et al. (2001b), Petrov & Kozack (2007), and Chou et al. (2013). While RW Aur A is associated with a resolved companion 1.5" away (RW Aur B; e.g., Joy & van Biesbroeck 1944; Reipurth & Zinnecker 1993; White & Ghez 2001; Bisikalo et al. 2012), a few spectroscopic studies have suggested that RW Aur A is itself a spectroscopic binary (e.g., Gahn et al. 1999; Petrov et al. 2001a).

2.2. Ry Tau

As with RW Aur A, Ry Tau is associated with a bipolar jet. St-Onge & Bastien (2008) have shown that the blueshifted jet extends out to at least 3" from the star. The redshifted jet is much fainter at this angular scale, probably due to obscuration by a dusty circumstellar disk (e.g., Isella et al. 2010) and/or a remnant envelope (Takami et al. 2013; Garufi et al. 2019), as is the case for many other low-mass pre-main-sequence stars (e.g., Eisloffel et al. 2000 for a review). St-Onge & Bastien (2008) have alternatively identified two bow shocks that are associated with the redshifted jet, 2.8" and 3.1" away from the star.

Spatially resolved imaging observations of the blueshifted jet have been made by several groups in H$_\alpha$ 6563 Å emission (St-Onge & Bastien 2008; Uyama et al. 2022), UV C IV emission (1548/1551 Å; Skinner et al. 2018), and low-excitation forbidden emission lines at optical ([O I] 6300 Å; Agra-Amboage et al. 2009) and NIR wavelengths ([Fe II] 1.644 μm; Coffey et al. 2015; Uyama et al. 2022). Garufi et al. (2019) have presented observations of all these lines, as well as NIR [S II] 1.029–1.037 μm and He I 1.083 μm lines. The presence of high-excitation lines, such as the H$_\alpha$, He I, and C IV lines, may be due to shocks that are more energetic than those of the jets that are associated with many other pre-main-sequence stars (Eisloffel et al. 2000; Hartigan et al. 2000). Skinner et al. (2011) have reported the probable detection of X-ray emission in the jet.

Most of these observations at optical and NIR wavelengths have been made at high angular resolutions comparable to or better than 0.5", with the best resolutions being at 0.03–0.05" (Garufi et al. 2019; Uyama et al. 2022), using the Wide Field and Planetary Camera 2 and STIS on the HST, CFHT-OASIS, GEMINI-NIFS, the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) on the Very Large Telescope (VLT), and the Visible Aperture Masking Polarmetric Interferometer for Resolving Exoplanetary Signatures on Subaru, with the Subaru Coronagraphic Extreme AO (SCExAO). In the images obtained by St-Onge & Bastien (2008), the blueshifted jet consists of several knots at $\sim$30" scale, although the jet structures are not clear close to the star, due to the bright stellar continuum. Garufi et al. (2019) and Uyama et al. (2022) have conducted integral field spectroscopy, which minimizes the stellar continuum emission, revealing the presence of a few jet knots within $\sim$1" of the star.

Skinner et al. (2018) have revealed the presence of a faint redshifted jet within 0.8" of the star, which has not been identified by any of the above high-resolution observations at optical and NIR wavelengths. None of these high-resolution observations have shown the presence of a close companion within 1" of the star.

Agra-Amboage et al. (2009) and Coffey et al. (2015) have measured the velocity of the blueshifted jet from $-60$ to $-90$ km s$^{-1}$ in lowly excited forbidden lines ([O I], [Fe II]). This contrasts with the observations by Skinner et al. (2018), who measured $-136 \pm 10$ km s$^{-1}$ in the C IV lines. This discrepancy indicates

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17 The detector for HST-STIS.
the presence of multiple velocity components traced by emission lines at different excitation conditions.

This star has long been subject to extensive photometric monitoring, exhibiting peculiar photometric variations with a V-band amplitude $\Delta m_V \sim 2.5$ mag (e.g., Herbst & Stine 1984; Zajtseva et al. 1985; Bouvier et al. 1993; Herbst et al. 1994; Petrov et al. 1999; Grankin et al. 2007; Garufi et al. 2019). As for RW Aur A, many of these authors have attributed the photometric variabilities to dust occultations, while Garufi et al. (2019) have shown a possible correlation between photometric variability and jet knot ejections, suggesting that it is related to time-variable mass accretion. This star is also known to exhibit remarkable variabilities in optical line profiles (Petrov et al. 1999, 2019, 2021; Chou et al. 2013). The observed timescales of the line profile changes range from a few days to years.

2.3. DG Tau

The jet from DG Tau has been extensively observed for at least 40 yr. The blueshifted jet was first identified as a single knot 8″ away from the star (Mundt & Fried 1983). Later on, a number of spectro-imaging observations at subarcsecond resolutions were conducted in the optical (H, [O I] 6300/6363 Å, [S II] 6712/6731 Å, and [N II] 6548/6583 Å—Kepler et al. 1993; Dougados et al. 2000; Lavalle-Fouquet et al. 2000; Coffey et al. 2007; Liu et al. 2016) and NIR ([Fe II] 1.644 μm; Pyo et al. 2003; Agra-Amboage et al. 2011; White et al. 2014b), using CFHT-PUEO/OASIS/STIS2, HST-STIS, Subaru-IRCS, the Spectrograph for Integral Field Observations in the Near Infrared (SINFONI) on the VLT, and Gemini-NIFS. In contrast to the similar observations for RW Aur A and RY Tau, these observations with 0″1 resolutions have revealed internal structures in the jet within 1″, which look similar to bow shocks and bubbles (Bacciotti et al. 2000; Agra-Amboage et al. 2011; White et al. 2014b). These observations have simultaneously revealed an “onion-like” kinematic structure, with the fastflow at the jet axis surrounded by slower flow components. The presence of the optical [Ne III] (3869 Å; Liu et al. 2016) and IR He I (1.083 μm; Takami et al. 2002a) lines indicates the more energetic nature of the jet compared to those associated with many other pre-main-sequence stars. The measured radial velocities of the jet in the above literature range from −120 to −350 km s$^{-1}$ (see Section 5.1.1 for details).

X-ray emission in the jet has been observed by Güdel et al. (2005), Güdel et al. (2008), and Schneider & Schmitt (2008). Güdel et al. (2011) and White et al. (2014b) have reported the presence of a stationary shock component at 0″02 from the star, based on multi-epoch studies. Other detailed studies of the physical conditions of the jet include those by Coffey et al. (2008), White et al. (2014a), and White et al. (2016). While many of the studies in the optical and NIR show only the blueshifted jet, Agra-Amboage et al. (2011), White et al. (2014a), and White et al. (2014b) have observed a faint redshifted bubble-like structure about 1″ away from the star, in the opposite direction from the blueshifted jet.

Grankin et al. (2007) measured a V-band photometric variability of the star of $\Delta m_V \sim 2.5$ mag over 20 yr. Chou et al. (2013) observed relatively stable optical line profiles over a few months in 2010, but found some differences with the literature, based on the observations from 1983 to 1996, perhaps due to long-term variabilities over 10–30 yr scales. As for RY Tau, the above high–angular resolution observations at optical and NIR wavelengths have not shown the presence of a close binary companion.

3. Observations and Data Reduction

The observations were made using Gemini-NIFS, VLT-SINFONI, and the OH-Suppressing Infrared Imaging Spectrograph (OSIRIS) on Keck, with AO. Table 2 summarizes the instrument specifications, with the selected gratings and integral field units. The NIFS and SINFONI spectra cover several [Fe II] lines, including those at 1.644, 1.534, 1.600, 1.664, 1.712 and 1.745 μm. The OSIRIS spectra cover a few major [Fe II] lines, from 1.59 to 1.67 μm. Spectral resolutions of 3000–5300 are not sufficient for resolving the internal kinematics of the target jets in many cases, but they are optimal for obtaining images of emission lines with high signal-to-noise ratios (Section 4.4).

Table 3 shows the log of the observations for the three target stars. Many of the spectra were obtained using NIFS in photometric conditions, with a typical angular resolution of 0″10–0″15. The data from 2012 to 2013 were obtained using an occulting disk at the focal plane with a 0″2 diameter. The other data were obtained without an occulting mask, with short exposures, to avoid the saturation of the stellar continuum.

For many of the observations, the star was placed near the edge of the field of view (FOV), to maximize the coverage of the jet over a large spatial area. RW Aur A is associated with a bipolar jet, and we covered the redshifted jet (i.e., the brighter jet). For RY Tau and DG Tau, we covered the blueshifted jet, as the redshifted counterpart was faint or absent, due to obscuration by a circumstellar disk (Section 2).

The data were reduced using the pipelines provided by the observatories, as well as software that we developed, using PyRAF, numpy, scipy, and astropy on python. For the NIFS data, we used the Gemini IRAF package for sky subtraction, flat-fielding, the first stage of bad pixel removals, 2D–3D transformations of the spectral data, and wavelength calibration. We then used our own software to stack the data cubes for each date, telluric correction, flux calibration, the extraction of the cube for the target emission line, the additional removal of bad pixels, and continuum subtraction. We have also corrected for flux loss with the halo of the point-spread function (PSF), as the jet structures that we are interested in are significantly smaller than the halo of the PSF, which extends over a >0″5 scale. We used identical processes for the SINFONI and

| Telescope and Instrument | Operation | IFU and (Selected) Sampling | Grating | Spectral Coverage (μm) | Spectral Resolution R | Field of View (FOV) |
|--------------------------|-----------|-----------------------------|---------|-----------------------|----------------------|---------------------|
| Gemini-NIFS              | Queue     | Slit Slicer, 0″1 × 0″04     | H       | 1.49–1.80             | 5300                 | 3″0 × 3″0           |
| VLT-SINFONI              | Queue     | Slit Slicer, 0″1 × 0″05     | H       | 1.45–1.85             | 3000                 | 3″6 × 3″3           |
| Keck-OSIRIS              | Classical | Lenslet, 0″05              | Hα      | 1.59–1.67             | 5800                 | 3″2 × 2″4           |

Table 2

Instruments

Table 3
Log of the Observations

| Star     | Date     | Instrument | Run ID (PI) | Photometrically Accurate | $t_{\text{exp}}$ (s) | $n_{\text{exp}}$ | Core FWHM (arcseconds) | $f_{\text{core}}$ | Range of Integration $v$ (km s$^{-1}$) | $Y$ (arcseconds) | Notes |
|----------|----------|------------|-------------|--------------------------|----------------------|------------------|------------------------|-----------------|----------------------------------------|------------------|-------|
| RW Aur A | 2012 Oct 20 | NIFS$^a$ | GN-2012B-Q-99 (Beck) | o | 600 | 9 | 0.16 | 0.61 | 30 to 180 | -0.15 to +0.15 | |
|          | 2014 Feb 28 | NIFS | GN-2014A-Q-29 (Günther) | o | 60 | 12 | 0.15 | 0.48 | 30 to 180 | -0.15 to +0.15 | |
|          | 2014 Dec 29 | NIFS | GN-2014B-Q-18 (Günther) | o | 84 | 20 | 0.15 | 0.45 | 30 to 180 | -0.15 to +0.15 | |
|          | 2017 Feb 15 | NIFS | GN-2017A-FT-1 (Takami) | o | 55 | 36 | 0.15 | 0.49 | 30 to 180 | -0.15 to +0.15 | |
|          | 2017 Dec 8 | SINFONI | 2100.C-5015(A) (Takami) | | 4 | 140 | 0.10 | 0.24 | -20 to 230 | -0.15 to +0.15 | |
|          | 2017 Dec 11 | SINFONI | 2100.C-5015(A) (Takami) | | 4 | 140 | 0.10 | 0.26 | -20 to 230 | -0.15 to +0.15 | |
|          | 2018 Aug 21 | NIFS | GN-2018B-Q-141 (Takami) | | 55 | 17 | 0.14 | 0.46 | 30 to 180 | -0.15 to +0.15 | |
|          | 2018 Aug 31 | NIFS | GN-2018B-Q-141 (Takami) | o | 55 | 3 | 0.12 | 0.51 | 30 to 180 | -0.15 to +0.15 | |
|          | 2018 Sep 16 | NIFS | GN-2018B-Q-141 (Takami) | | 55 | 19 | 0.12 | 0.50 | 30 to 180 | -0.15 to +0.15 | |
|          | 2019 Oct 7  | NIFS | GN-2019B-Q-132 (Takami) | | 55 | 36 | 0.16 | 0.46 | 30 to 180 | -0.15 to +0.15 | |
|          | 2021 Feb 3  | OSIRIS | S21A0039N/S364 (Takami) | o | 24 | 30 | 0.05–0.10$^f$ | ~0.3$^f$ | 10 to 190 | -0.15 to +0.15 | |
| RY Tau   | 2012 Oct 27 | NIFS$^c$ | GN-2012B-Q-99 (Beck) | o | 600 | 10 | 0.14 | 0.52 | -170 to -40 | -0.25 to +0.25 | |
|          | 2014 Feb 28 | NIFS | GN-2014A-Q-29 (Günther) | o | 15 | 30 | 0.18 | 0.35 | -170 to -40 | -0.25 to +0.25 | |
|          | 2014 Dec 29 | NIFS | GN-2014B-Q-18 (Günther) | o | 15 | 54 | 0.18 | 0.46 | -170 to -40 | -0.25 to +0.25 | |
|          | 2017 Feb 18 | NIFS | GN-2017A-FT-1 (Takami) | o | 15 | 105 | 0.12 | 0.46 | -170 to -40 | -0.25 to +0.25 | |
|          | 2018 Aug 17 | NIFS | GN-2018B-Q-141 (Takami) | o | 15 | 99 | 0.15 | 0.37 | -170 to -40 | -0.25 to +0.25 | |
|          | 2019 Oct 23 | NIFS | GN-2019B-Q-132 (Takami) | o | 15 | 108 | 0.13 | 0.53 | -170 to -40 | -0.25 to +0.25 | |
|          | 2021 Feb 3  | OSIRIS | S21A0039N/S364 (Takami) | o | 19 | 46 | 0.05–0.10$^f$ | ~0.4$^f$ | -160 to -30 | -0.2 to +0.2$^g$ | |
| DG Tau   | 2013 Feb 9  | NIFS$^c$ | GN-2012B-Q-32 (McGregor) | o | 600 | 6 | 0.16 | 0.61 | -240 to -70 | -0.3 to +0.3 | |
|          | 2014 Feb 28 | NIFS | GN-2014A-Q-29 (Günther) | o | 45 | 12 | 0.12 | 0.50 | -240 to -70 | -0.3 to +0.3 | |
|          | 2014 Dec 29 | NIFS | GN-2014B-Q-18 (Günther) | o | 45 | 27 | 0.14 | 0.37 | -240 to -70 | -0.3 to +0.3 | |
|          | 2017 Feb 17 | NIFS | GN-2017A-FT-1 (Takami) | o | 25 | 72 | 0.11 | 0.44 | -240 to -70 | -0.3 to +0.3 | |
|          | 2017 Dec 22 | SINFONI | 2100.C-5015(A) (Takami) | | 4 | 140 | 0.11 | 0.18 | -240 to -40 | -0.3 to +0.3 | |
|          | 2017 Dec 25 | SINFONI | 2100.C-5015(A) (Takami) | | 4 | 140 | 0.11 | 0.20 | -240 to -40 | -0.3 to +0.3 | |
|          | 2018 Nov 27 | NIFS | GN-2018B-Q-141 (Takami) | o | 25 | 72 | 0.12 | 0.48 | -240 to -70 | -0.3 to +0.3 | |
|          | 2019 Oct 17 | NIFS | GN-2019B-Q-132 (Takami) | o | 25 | 84 | 0.16 | 0.37 | -240 to -70 | -0.3 to +0.3 | |

Notes:

$^a$ With an absolute photometric accuracy of <10%.

$^b$ Fractional flux of the core of the PSF (see the text).

$^c$ For analysis in Section 4.

$^d$ Across the jet axis.

$^e$ The central star was masked using an occulting mask with 0.5 diameter.

$^f$ Less accurate, due to nonlinear response at the brightest pixels. We have also used data with short exposures to derive these values.

$^g$ Offset by 0.15 for knot “E” for Figure 1, in order to cover the emission (Section 4.2).
OSIRIS data, except that the data stacking was done using the observatory pipeline.

Some queue observations were split into different nights over a timescale of a month. These data were stacked for individual fall–winter periods. For each data set, we identified possible changes in the brightness of the knots over a month, perhaps due to changes in shock conditions on a month scale (Section 5.1.2). Detailed analysis of the variation of the jet emission on this timescale is beyond the scope of this study. We assume that the possible changes in jet emission are independent of the variabilities of mass accretion and/or the optical emission lines close to the star, which also show such short-term variabilities (Section 5.1.4). This is because these activities cannot physically interact with the jet knots once they move away from the star.

For the SINFONI and OSIRIS data, which have spectral resolutions lower than NIFS, we have made additional corrections of slight errors in the wavelength calibration, using the telluric and photospheric absorption lines. As a result, we are confident in the accuracy of the measured absolute velocities at about $a \pm 10$ km s$^{-1}$ level for the NIFS data and at $a \pm 20$ km s$^{-1}$ level for the SINFONI and OSIRIS data.

For RW Aur A, we found a marginal error ($\sim 1^\circ$) in the actual image position angle (PA) for those set for the NIFS, SINFONI, and OSIRIS observations. This was corrected by measuring the PA toward the binary companion RW Aur B ($d \sim 1.5\,\text{yr}^{-1}$). See Takami et al. (2020) for details. As RY Tau and DG Tau are single stars, we regard the above error as a typical uncertainty of the jet PAs. This error probably explains the slightly different jet PAs for different epochs, which hamper reliable analysis. For those with relatively large PA offsets, we visually inspected the offsets and adjusted them (see Figures 1–3) for our positional analysis along the jet axis in Section 4.

For this paper, we limit our analysis of the spatial distribution and kinematics to the [Fe II] 1.644 $\mu$m emission, and our analysis of the intensity ratios at the peaks of the knots to the [Fe II] 1.644, 1.533, and 1.600 $\mu$m emission, due to limited signal-to-noise ratios. Some velocity-integrated maps for [Fe II] 1.644 $\mu$m have already been published by Takami et al. (2020) and Uyama et al. (2022). Takami et al. (2020) used all the data for RW Aur A, but for the most recent epoch (2021 February 3), and performed comparisons with jet knot ejections as well as optical photometry and spectroscopy to investigate a physical link between mass accretion and ejection. Uyama et al. (2022) used the velocity-integrated maps for RY Tau for the two most recent epochs (2019 October 23 and 2021 February 3) and performed comparisons with the jet knots seen in the H$_\alpha$ emission.

## 4. Results

Figures 1–3 show the velocity-integrated maps and the position–velocity (PV) diagrams of the [Fe II] 1.644 $\mu$m emission for the redshifted jet from RW Aur A, the blueshifted jet from RY Tau, and the blueshifted jet from DG Tau, respectively. In each figure, we place the maps and diagrams in chronological order, from top to bottom. In Table 3, we tabulate the ranges of the velocity and spatial integrations, which we have carefully adjusted, to cover most of the line emission while also maximizing the signal-to-noise ratio. The [Fe II] 1.533 and 1.600 $\mu$m emissions, which we will analyze later for intensity ratios, have spatial distributions very similar to the 1.644 $\mu$m emission, but with low signal-to-noise ratios, due to their faint natures.

In these figures, we identify chains of knotty structures, as in previous spectro-imaging at UV to NIR wavelengths (see Section 2). In this section, we analyze these knots, tentatively attributing them to moving knots, as in several earlier studies (see Table 7 in Section 5.1.1). In Section 4.1, we identify these knots, then analyze their proper motions and the time intervals of the ejections. In Section 4.2, we briefly summarize their spatial extension across the jet axis. In Section 4.3, we statistically analyze their peak intensities, intensity ratios, and inferred electron densities. In Section 4.4, we summarize the observed radial velocities and perform comparisons with the tangential velocities inferred from Section 4.1.

Some knots may alternatively be attributed to “stationary shocks,” without proper motions, rather than to moving knots. We will discuss this issue in Section 5.2.

### 4.1. Identification of Moving Knots

To easily identify the moving jet knots that have been observed at different epochs, we apply spatial offsets to individual panels along the jet axis, corresponding to $0/2\,\text{yr}^{-1}$, $0/3\,\text{yr}^{-1}$, and $0/5\,\text{yr}^{-1}$ for RW Aur A, RY Tau, and DG Tau, respectively, from the most recent epoch of the observations.

We identify at least five peaks for the RW Aur A jet (labeled A, B, D, E, and F in Figure 1) and at least eight peaks for the RY Tau jet (labeled A to H in Figure 2). The presence of these knots in the RW Aur A jet has previously been reported by Takami et al. (2020), using the same data sets obtained from 2012 to 2019. Following careful analysis, we additionally identify the probable faint knot C in this jet. The jet knots G and H in the RY Tau jet were reported by Uyama et al. (2022; labeled A and B in their paper). For the DG Tau jet, we identify at least two peaks (C–E), another possible component (B), and a large elongated structure downstream (A), in Figure 3.

Tables 4–6 show the positions of these knots at different epochs, measured as follows. We first integrated the intensity distribution across the jet axis and over the velocities for the ranges shown in Table 3 (i.e., the same ranges that were used for the velocity-integrated maps and the PV diagrams in Figures 1–3). We then applied a polynomial fit for 4–6 positions near the peak and measured the position at the intensity peak. For each knot, we then fit these offsets from the star as a function of the date, using a straight line, and derived their proper motions and the date at the origin (Figure 4).

There is no straightforward definition of the uncertainty of the measurement of each jet knot position using the above method. We therefore regard the standard deviations of the individual measurements from the fitted straight lines as the typical uncertainties, which are also tabulated for each knot in Tables 4–6.

To derive the uncertainties, we need at least three epochs of observations. We use the measurements of the earliest four epochs of observations, when available. We have more epochs of observations for Knot D in the RW Aur A jet and knot C, but we exclude those in the downstream for the better accuracy of the measurements for the dates at the origin.

One might suspect that the measured knot positions are affected by the selected spatial range across the jet axis and velocity range. To investigate this, we have derived knot positions by increasing/decreasing each range by 30%. This analysis yielded a typical positional difference of $0/0.007$, which
has little effect on the fitting parameters tabulated at the bottoms of Tables 4–6. The changes in the fitting parameters following this analysis are significantly smaller than the uncertainties shown in Tables 4–6.

As shown in Tables 4–6 and Figure 4, the knots in the jets would have different tangential velocities for the RW Aur A and RY Tau jets: these are, $0.16-0.29\ yr^{-1}$ (knots B–E; corresponding to 120–220 km $s^{-1}$) and $0.2-0.4\ yr^{-1}$ (knots A, B, C, E, F, and G; corresponding to 120–240 km $s^{-1}$), respectively. For the DG Tau jet, the epochs of observation are not sufficient to investigate the variations of the tangential velocities between the knots.

For knot F in the RW Aur jet, one may infer a proper motion of $0.08\ yr^{-1}$, based on the peak positions. This value is significantly smaller than the others ($0.19-0.29\ yr^{-1}$; see Figure 4 and Table 4). As shown in Figure 1, this knot looks elongated in the most recent epoch (2021 February 3). We cannot exclude the possibility that another new knot has emerged in this epoch, and is apparently near the original knot F, making a single elongated knot-like structure in the images with the given angular resolution. Observations for a later epoch would allow us to prove or reject this explanation.

The knots with large proper motions may have collided, or may collide in the future, with others downstream. Figure 2 shows that Knot D from RY Tau may have collided with Knot C in 2016–2017, but it is not conclusive, due to the insufficient epochs of measurement for Knot D. Figure 4 suggests that Knots C, D, and E from RW Aur A will collide in the next few years, at $\sim3\''$ from the star.

In Tables 4–6, we also list the epochs of jet knot ejections at the star, based on proper-motion measurements, as well as their time intervals. The intervals for the jet knot ejections from RW Aur A and RY Tau show irregular time intervals, between 300–2000 and 300–1200 days, respectively. We do not have sufficient epochs of observations to investigate whether the time intervals are irregular or not for the DG Tau jet. However, the measured intervals of 1300–1500 days are different from those inferred from previous studies: $\sim1800$ or $\sim900$ days, or a combination of these two, between 1980 and 2005 (Pyo et al. 2003; Agra-Amboage et al. 2011; Rodriguez et al. 2012; Pyo et al. 2013; Agra-Amboage et al. 2011; Rodriguez et al. 2012; Pyo et al. 2013).
White et al. (2014b). This discrepancy suggests that the jet knot ejections are irregular over a timescale of \( \sim 40 \text{ yr} \).

Figure 5 shows how the observed intensity distribution along the jet axis changes with time at the positions of the individual knots. The data obtained using SINFONI and OSIRIS are not included, as higher angular resolutions (see Table 3) make it more difficult to investigate the actual time variations of the spatial structures. As for the measurements of the peak positions, we spatially integrate the intensity across the jet axis. We then arbitrarily scale the intensity distributions and show them in chronological order, from top to bottom, with each panel being organized around an individual knot. For some knots and epochs, we were not able to measure the peak positions using the method described above. For these, we have adopted values based on the proper-motion measurements.

Figure 5 shows that the knots have a spatial extent along the jet comparable to the angular resolution (typically 0\(\cdot\)15 for the plotted data; see Table 3). Many of these knots are smeared for later epochs: these are knot E from RW Aur A; knots A, B, and C from RY Tau; and knots C and D from DG Tau. Such a trend is less clear for the remaining knots.

4.2. Spatial Structures across the Jet Axis

For all jets, the emission across the jet axis is marginally resolved, with FWHMs being up to 0\(\cdot\)4–0\(\cdot\)5, two to three times larger than the angular resolution. These FWHM values are similar to those from previous observations of the same jets with the same emission lines (Agra-Amboage et al. 2011; Garufi et al. 2019) and optical emission lines (Bacciotti et al. 2000; Dougados et al. 2000; Woitas et al. 2002; Agra-Amboage et al. 2009; Liu & Shang 2012; Garufi et al. 2019).

The [Fe II] 1.644 \(\mu\)m emission in our velocity-integrated maps shows a Gaussian-like or a symmetric triangular distribution, except for structure A in the DG Tau jet, for which we find asymmetric profiles in some positions. In Figure 3, the spatial distribution of this structure is similar to the asymmetric bow shock modeled by Raga et al. (2001).

Some line profiles are associated with faint and more extended emission, particularly bright jet regions. While this could be real emission at the observed positions, we cannot currently exclude the possibility that it is due to halos associated with the PSFs.

For RW Aur A and DG Tau, the observed knots are closely aligned along a single PA. In contrast, Figure 2 shows recognizable offsets from a single jet axis for the RY Tau jet. The most remarkable offsets are seen for knot E, as observed in 2019 and 2021, which is offset from the jet axis shown in Figure 2 by about \( \sim 0\cdot1 \). The PA of knot E from the star is different from that of knot G by \( \sim 8\cdot \). In 2014, we also identify a small offset for B, whose PA is different to that of C by 3\(^{\circ}–\)6\(^{\circ} \). For RW Aur, we also identify a marginal offset for knot B,
observed in 2012 and early 2014. In the latter epoch, the PA of the knot B is different to that of A by \(\sim 2^\circ\).

The differences in directions observed in the RY Tau jet may be due to the wiggling motions of the jet (Lavalley-Fouquet et al. 2000; Raga et al. 2001; Garufi et al. 2019; Uyama et al. 2022). In particular, Garufi et al. (2019) observed the RY Tau jet over a \(\sim 6''\) scale in 2017 and 2019, identifying a similar pattern. These authors measured a jet PA of 290\(^\circ\) at the base of the jet and for an elongated structure 5''–6'' away from the star, and a jet PA of 295\(^\circ\) for a knot 3''–4'' away from the star. This pattern is explained as an outer extension of the jet wiggling pattern that is seen in our 2017 and 2019 images, in which the jet shows a smaller PA between knots C and F (Figure 2).

Garufi et al. (2019) discussed the following two possibilities for the origin of the jet wiggling, using the observed spatial distributions of the jet and its velocity: (1) the orbital motion of the primary star induced by a stellar companion (e.g., Anglada et al. 2007); and (2) the precession of the inner disk (i.e., where the jet is launched), induced by a substellar companion, whose orbit is misaligned with the outer disk plane (e.g., Zhu 2019). Garufi et al. (2019) excluded the first scenario, because the companion required to explain the observed jet wiggling \((M_{\ast} = 1.1 \, M_\odot, \, d \sim 0''1)\) has not been detected by high-resolution imaging observations to date (Section 2.2). These authors demonstrated that the second scenario would work, though: a substellar companion that explained the observed jet wiggling would be too faint and/or too close to the primary star to be detected by these observations. The alternative scenario, which was not discussed by Garufi et al. (2019), is that the precession of the disk is induced by magnetic torques associated with the jet/outflow, resulting in a warping instability in the inner disk (Lai 2003; Erkal et al. 2021a).

### 4.3. Peak Intensities and Intensity Ratios

Figures 6 and 7 show the 1.644 \(\mu\)m peak intensities of the individual knots as a function of the projected distance to the star and the observed date, respectively. To minimize the effects of different angular resolutions, we measured the peak intensity for each knot in a 0''15 × 0''15 area. In the same figures, we also plot the 1.533/1.644 \(\mu\)m and 1.600/1.644 \(\mu\)m intensity ratios at the 1.644 \(\mu\)m intensity peaks. For these figures, we selected the data points for each line using the following criteria: (1) we identify the intensity peaks in the velocity-integrated maps; and (2) the measured intensities or intensity ratios are above 3\(\sigma\) levels. Furthermore, we use the data obtained under photometric conditions only for the 1.644 \(\mu\)m peak intensities.

In Figures 6 and 7, the peak intensities of the individual knots tend to decrease as the Julian date (JD) and the distance to the star increase, by a factor of up to \(\sim 30\), during the time of our observations. In Figure 6, the peak intensities of the different knots show a fairly good correlation for many of the...
| Date         | A   | B     | C         | D         | E         | F         |
|--------------|-----|-------|-----------|-----------|-----------|-----------|
| 2012 Oct 20  | 1°349 | 1°021 | ...       | ...       | 0°339     | ...       |
| (v_{rad}; km s^{-1}) | (110 ± 10) | (86 ± 10) | ...       | (85 ± 10) | ...       | ...       |
| 2014 Feb 28  | ...   | 1°344 | 0°928     | 0°638     | ...       | ...       |
| (v_{rad}; km s^{-1}) | ...     | (79 ± 10) | (72 ± 10) | (79 ± 10) | ...       | ...       |
| 2014 Dec 29  | ...   | ...   | ...       | ...       | 0°808     | ...       |
| (v_{rad}; km s^{-1}) | ...     | ...     | ...       | ...       | ...       | ...       |
| 2017 Feb 15  | ...   | 1°833 | ...       | 1°136     | ...       | ...       |
| (v_{rad}; km s^{-1}) | ...     | (78 ± 10) | ...       | (86 ± 10) | ...       | ...       |
| 2017 Dec     | ...   | 2°053 | ...       | 1°372     | 0°394     | ...       |
| (v_{rad}; km s^{-1}) | ...     | ...     | ...       | ...       | ...       | ...       |
| 2018 Aug–Sep | ...   | ...   | ... a     | ... a     | (128 ± 20) | ...       |
| (v_{rad}; km s^{-1}) | ...     | ...     | ... a     | ... a     | ... a     | ... a     |
| 2021 Feb 3   | ...   | ...   | ... a     | ... a     | (87 ± 20) | (98 ± 20) |
| (v_{rad}; km s^{-1}) | ...     | ...     | ... a     | ... a     | ... a     | ... a     |

Notes.

a The signal-to-noise ratio is too low for reliable measurements.

b Not currently reliable, as it is not clear whether the tabulated position for 2021 February 3 is for knot F as observed in 2019 October 7. See the text for details.

| Date         | A   | B     | C         | D         | E         | F         | G         | H         |
|--------------|-----|-------|-----------|-----------|-----------|-----------|-----------|-----------|
| 2012 Oct 27  | 1°157 | 0°670 | 0°272     | ...       | ...       | ...       | ...       | ...       |
| (v_{rad}; km s^{-1}) | (-92 ± 10) | (-99 ± 10) | (-120 ± 10) | ...       | ...       | ...       | ...       | ...       |
| 2014 Feb 28  | 1°428 | 1°084 | 0°716     | ...       | ...       | ...       | ...       | ...       |
| (v_{rad}; km s^{-1}) | (-104 ± 10) | (-100 ± 10) | (-122 ± 10) | ...       | ...       | ...       | ...       | ...       |
| 2014 Dec 29  | 1°285 | 1°006 | 0°690     | ...       | ...       | ...       | ...       | ...       |
| (v_{rad}; km s^{-1}) | (-95 ± 10) | (-113 ± 10) | (-117 ± 10) | ...       | ...       | ...       | ...       | ...       |
| 2017 Feb 18  | ...   | ...   | ... 1°560 | ... 0°360 | ...       | ...       | ...       | ...       |
| (v_{rad}; km s^{-1}) | ...     | ...     | ... 1°560 | ... 0°360 | ...       | ...       | ...       | ...       |
| 2018 Aug 17  | ...   | ...   | ... 2°038 | ... 0°942 | ...       | ...       | ...       | ...       |
| (v_{rad}; km s^{-1}) | ...     | ...     | ... 2°038 | ... 0°942 | ...       | ...       | ...       | ...       |
| 2019 Oct 23  | ...   | ...   | ... 2°365 | 1°414     | 0°833     | 0°450     | ...       | ...       |
| (v_{rad}; km s^{-1}) | ...     | ...     | ... 2°365 | 1°414     | 0°833     | 0°450     | ...       | ...       |
| 2021 Feb 3   | ...   | ...   | ... 1°878 | 1°202     | 0°843     | 0°413     | ...       | ...       |
| (v_{rad}; km s^{-1}) | ...     | ...     | ... 1°878 | 1°202     | 0°843     | 0°413     | ...       | ...       |

Notes.

a The uncertainties are not clear due to the limited epochs of the observations.
b The interval from the second last ejection (C), as we were not able to measure that for the last ejection (D).

correlations from RW Aur A and for all those from RY Tau. In the top panels of Figure 7, the peak intensities measured for the individual knots show different inclinations, i.e., different timescales for intensity decays, in particular for the jet knots from RY Tau and DG Tau. In the case of knot D from RW Aur A, the peak intensity decreases by a factor of ~10 during the first ~800 days, but by a factor of ~3 during the subsequent ~1300 days. In contrast, the measured peak intensities in the
RY Tau jet marginally increased for knot A and knot B between JD = 2,456,228 and 2,456,716, both by a factor of $\sim 1.2$.

To further discuss the decay timescale of the emission, we define the timescale $t_{\text{decay}}$ based on the following equation:

$$I_t = I_0 \exp(-t/t_{\text{decay}}),$$  

(1)

where $I_0$ and $I_t$ are the peak intensities of a knot for two subsequent epochs of observation and $t$ is the time interval of these epochs. Figure 8 shows the number distributions, excluding the cases for which the peak intensities marginally increased. Most of these are distributed between 300 and 3600 days, with a median value of $\sim 1000$ days.

In Figures 6 and 7, we find observed 1.533/1.644 $\mu$m and 1.600/1.644 $\mu$m intensity ratios of 0.1–0.35 and 0.08–0.27, respectively. To the right of each panel for the intensity ratio, we mark the corresponding electron densities as calculated by Nisini et al. (2002), Pesenti et al. (2004), and Takami et al. (2006). These indicate that the electron densities at the intensity peaks range between $3 \times 10^{2}$ and $1 \times 10^{3}$ cm$^{-3}$. The line ratios and electron densities measured in the DG Tau and RW Aur A jets are similar to those from previous observations of the same jets (Bacciotti et al. 2000; Lavalley-Fouquet et al. 2000; Dougados et al. 2002; Woitas et al. 2002; Coffey et al. 2008; Melnikov et al. 2009; Agra-Amboage et al. 2011; White et al. 2014b).

In Figure 6, the intensity ratios (and therefore the electron densities) decrease downstream for the DG Tau jet, but this trend is not very clear for the others, perhaps because of modest signal-to-noise ratios. Again, this trend has also been measured for the DG Tau jet before, by Lavalley-Fouquet et al. (2000), Dougados et al. (2002), and White et al. (2014b). In Figure 7, the peak intensities of knot D from DG Tau appear to decrease with time. While a similar trend is observed for some of the other knots from all the stars, a better signal-to-noise ratio will be required for confirmation.

Figure 9 shows the correlation between the peak intensity and the FWHM of the jet width for the individual knots. We use data obtained under photometric conditions only, as for the plots of the peak intensities in Figures 6 and 7. We have not applied the deconvolution procedure, and we indicate a typical PSF size (0\''15; see Table 3) using the vertical black dashed lines in the individual panels. In the figure, the peak intensities and the FWHMs show a negative correlation, implying that the compact knots show larger surface brightnesses. For the jets from RW Aur A and RY Tau, the measured ranges of the FWHMs (a factor of 2–3) are significantly smaller than those for the peak intensities (a factor of 10–100). In contrast, those

Table 6

| Date            | C      | D      | E      |
|-----------------|--------|--------|--------|
| 2013 Feb 9      | ...    | ...    | ...    |
| ($v_{\text{rad}}$; km s$^{-1}$) | ...    | ...    | ...    |
| 2014 Feb 28     | $0^\circ 525$ | ...    | ...    |
| ($v_{\text{rad}}$; km s$^{-1}$) | $(-142 \pm 10)$ | ...    | ...    |
| 2014 Dec 29     | $0^\circ 609$ | $0^\circ 305$ | ...    |
| ($v_{\text{rad}}$; km s$^{-1}$) | $(-134 \pm 10)$ | $(-120 \pm 10)$ | ...    |
| 2017 Feb 17     | ...    | $0^\circ 510$ | ...    |
| ($v_{\text{rad}}$; km s$^{-1}$) | ...    | $(-152 \pm 10)$ | ...    |
| 2017 Dec        | ...    | $0^\circ 693$ | ...    |
| ($v_{\text{rad}}$; km s$^{-1}$) | ...    | $(-143 \pm 20)$ | ...    |
| 2018 Nov 27     | ...    | $0^\circ 818$ | $0^\circ 281$ |
| ($v_{\text{rad}}$; km s$^{-1}$) | $(-136 \pm 10)$ | $(-141 \pm 10)$ | ...    |
| 2019 Oct 17     | ...    | $0^\circ 938$ | $0^\circ 383$ |
| ($v_{\text{rad}}$; km s$^{-1}$) | $(-140 \pm 10)$ | $(-155 \pm 10)$ | ...    |

$\nu_{\text{un}}$ (arcsec yr$^{-1}$) | $0.101^a$ | $0.136 \pm 0.016$ | $0.115^a$

$\nu_{\text{rad}}$ (km s$^{-1}$) | $66^a$ | $89 \pm 13$ | $75^a$

JD-2,450,000 at Origin | 4816$^a$ | $6279 \pm 197$ | $7557^a$

Interval from Last Ejection (days) | ... | $\sim 1500$ | $\sim 1300$

Fitting Error (arcseconds) | ... | 0.038 | ...
ranges are similar for the jet from DG Tau—factors of $\sim 2$ and $\sim 3$ for the FWHMs and the peak intensities, respectively.

### 4.4. Radial versus Tangential Velocities

The radial velocity profiles at individual positions in the jet can be reasonably well fitted by a single Gaussian, with FWHMs comparable to the instrument resolution for all the jets and a majority of the epochs. In the jets from DG Tau and RY Tau, the FWHMs reach as close as 120–140 km s$^{-1}$ to the star in some epochs. Furthermore, some line profiles are associated with faint wing emission at low velocities, probably due to one or more of the following: (1) a slow wide-angled wind (see Eislöffel et al. 2000 for a review); (2) an onion-like kinematic structure in the jet, with a highly collimated central flow surrounded by slower components (Bacciotti et al. 2000); and (3) ambient gas entrained...
by the jet (Pyo et al. 2003; White et al. 2014b, 2016). We leave
detailed analysis of these components for possible future work,
due to the difficulties of analysis resulting from the limited
velocity resolution and their faint nature. Similarly, we also leave
a search for the spinning motions in the jet (e.g., Coffey et al.
2004, 2007, 2011, 2012, 2015; Lee et al. 2017; Erkal et al. 2021a)
for possible future work, because this study requires careful
analysis of radial velocities that are significantly smaller than the
instrument resolutions.

Using Gaussian fitting, we derive velocities in the jet of
70–130 km s\(^{-1}\) for RW Aur A, −70 to −120 km s\(^{-1}\) for RY
Tau, and −120 to −200 km s\(^{-1}\) for DG Tau. These vary
spatially within the jet, suggesting that the jet-launching
velocities vary on timescales of a few years or more, as was
the case for the tangential velocities that we discussed in
Section 4.1. In Tables 4–6, we list the radial velocities
measured at the peak positions of the knots. We do not find any
clear evidence for the time variation of the radial velocities for
any knot. For knot E in the RW Aur jet, the radial velocity may
have decreased from ∼120 to ∼90 km s\(^{-1}\) between 2017 and
2021, but the difference is still comparable to the uncertainties
for the measurements.

Figure 7 shows the correlations between the radial
velocities and the tangential velocities that we measured in
Section 4.1. The large uncertainties in the radial velocities
hamper our investigation into whether these two velocities are
correlated. We derive average jet inclination angles of
28° ± 2°, 29° ± 5°, and 59° ± 3° for the jet from RW Aur A, RY Tau, and DG Tau, respectively.

5. Discussion

In Section 4, we presented our results and analysis,
tentatively attributing the observed jet knots to “moving
knots.” In Section 5.1, we further discuss the moving knot
scenario, with their possible heating mechanisms. In
Section 5.2, we show that some knots in the inner regions
may be alternatively attributed to “stationary shocks,” rather
than to moving knots, as discussed in some previous studies.

5.1. The Moving Knot Scenario

In Section 5.1.1, we perform comparisons of the tangential
and radial velocities of the jet knots between our analysis in
Section 4 and the literature, as well as discuss their time
variations over a period up to ∼200 yr and the implications for
the moving knot scenario. In Section 5.1.2, we attempt to
attribute the observed trends to shocks, a popular interpretation
for jet knots. In Section 5.1.3, we discuss alternative
explanations for the physical nature of the moving jet knots. In
Section 5.1.4, we briefly discuss the implications for the
regular/irregular time intervals of the jet knot ejections.

5.1.1. Long-term Variation of Jet Velocities

In Section 5.1.1, we perform comparisons of the tangential
and radial velocities of the jet knots between our analysis in
Section 4 and the literature, as well as discuss their time
variations over a period up to ∼200 yr and the implications for
the moving knot scenario. In Section 5.1.2, we attempt to
attribute the observed trends to shocks, a popular interpretation
for jet knots. In Section 5.1.3, we discuss alternative
explanations for the physical nature of the moving jet knots. In
Section 5.1.4, we briefly discuss the implications for the
regular/irregular time intervals of the jet knot ejections.

In Table 7, we compare the measured proper motions
between this study and those from previous work. For the jets
from RW Aur A and RY Tau, the proper motions that we
measured are similar to those in the literature. In contrast, those
that we measured for the DG Tau jet are smaller than the values
in the literature, by a factor of ∼2.

In Table 8, we compare the radial velocities of the jet line
emission with the previous observations at subarcsecond
resolutions. In this table, we include the observations of the
[Fe II] 1.644 μm, [O I] 6300 Å, and [S II] 6731 Å lines only.
Figure 9. The correlation between the FWHMs across the jet and the peak intensities for the knots in the [Fe II] 1.644 μm emission. The FWHMs are measured without deconvolution of the observed PSFs. The vertical error bars are only shown when they are larger than the dots. The vertical dashed line at the left of each panel shows a typical angular resolution (0''15).

Figure 10. Correlations between the tangential and radial velocities for the individual jets. The dashed lines are based on the average of the inclinations of the ejections. Only the error bars for the tangential velocities that we were able to measure are shown (see Section 4.1 and Tables 4–6).

Table 7

| Star     | Proper Motion (arcsec yr⁻¹) | V_tan (km s⁻¹) | Angular Distance from the Star | Lines a | Approximate Years of Ejections from the Star | References b |
|----------|-----------------------------|----------------|-------------------------------|---------|--------------------------------------------|---------------|
| RW Aur A | 0.15–0.23                   | 110–170        | 0''3–20''                     | [Fe II], [S II], Hα | 1830–2000 | 1   |
|          | 0.16–0.24                   | 120–180        | 1''–3''                       | [S II]  | 1930–2000 | 2   |
|          | 0.16–0.29                   | 120–210        | 0''2–3''                      | [Fe II] | 2007–2020 | This work |
| RY Tau   | 0.3–0.4                     | 180–240        | 1''–6''                       | [Fe II] | 1980–2010 | 3   |
|          | 0.2–0.4                     | 120–240        | 0''2–2''5                     | [Fe II] | 2007–2020 | This work |
|          | ~0.3                        | ~200           | 0''15–1''                     | [Fe II], Hα | 2019–2021 | 4   |
| DG Tau   | 0.3                         | 200            | ~0''3                         | [O I]   | 1985      | 5   |
|          | 0.27–0.3                    | 180–200        | 0''1–3''5                     | various | 1995–2000 | 6   |
|          | 0.17–0.33                   | 110–220        | 0''2–1''4                     | [Fe II] | 1998–2004 | 7   |
|          | 0.10–0.14                   | 70–90          | 0''2–2''                      | [Fe II] | 2008–2020 | This work |

Notes.

a [Fe II] 1.644 μm, [S II] 6731 Å, and [O I] 6300 Å for the forbidden lines.

b (1) Berdnikov et al. (2017); (2) Lopez-Martin et al. (2003); (3) Garufi et al. (2019); (4) Uyama et al. (2022); (5) Dougados et al. (2000); (6) Pyo et al. (2003); and (7) White et al. (2014b).
These low-excitation lines have similar excitation conditions (e.g., Hollenbach & McKee 1989; Takami et al. 2002b; Hartigan et al. 2004b). We exclude observations of the other lines from this table, as a large difference in the excitation conditions may cause a systematic difference in the radial velocities (Skinner et al. 2018; Garufi et al. 2019; Erkal et al. 2021b).

For the DG Tau jet, the radial velocities that we measured from 2013 to 2019 are remarkably lower than the previous observations made between 1998 and 2009 (i.e., $-170$ to $-350$ km s$^{-1}$), as is also the case for the proper motions listed in Table 7. This trend was previously reported by Liu et al. (2016), based on limited epochs of observations, using data obtained in 1999 from the HST and ground-based spectro-imaging in 2010 with an angular resolution of $\sim 1''$. If the ejection velocities of the jet knots have decreased, the decreases in both the tangential and radial velocities over recent years can be explained, further supporting the moving knot scenario. Liu et al. (2016) pointed out that such a decrease may be related to the expansion of the stellar magnetosphere, if the jet is launched from the stellar magnetosphere (or the associated “X-point”; Shu et al. 2000).

In contrast, the jets from RW Aur A and RY Tau had similar velocities in the period of our observations (2000–2021) and in the past (1930–2010). The tangential velocities tabulated in Tables 4 and 5 vary between $120$–$210$ km s$^{-1}$ and $\sim 120$–$230$ km s$^{-1}$, respectively, measured during our observations of 2012–2021. The same physical mechanism that changes the velocity of the jet from DG Tau may also be responsible for these time variations, but on shorter timescales.

5.1.2. The Shock Heating/Cooling Scenario

Many authors favor the shock heating scenario as the heating mechanism of the jets that are close to active pre-main-sequence stars. This scenario is particularly favored for DG Tau, for which the jet structures close to the star are spatially resolved. Lavallee-Fouquet et al. (2000), Dougados et al. (2000), and Bacciotti et al. (2000) have resolved bow shock-like structures in the blueshifted jet at $1''$–$4''$ from the star. Pyo et al. (2003) observed a distinct low-velocity component ($v \sim -100$ km s$^{-1}$) close to a high-velocity jet knot $0''8$ from the star. The authors interpreted this component as gas that had been entrained by the jet knot. Lavallee-Fouquet et al. (2000) and Agra-Amboage et al. (2011) have demonstrated that the observed line intensity ratios at optical and NIR wavelengths are also consistent with the shock heating scenario, but more careful analysis may be necessary for gas within $70$–$100$ au (corresponding to $0''4$–$0''8$ for our target stars; Dougados et al. 2002). Other analyses that support the shock heating scenario include those by Dougados et al. (2002), Takami et al. (2002a), Hartigan et al. (2004a), and Garufi et al. (2019). As discussed in Section 4.2, structure A in Figure 3 is similar to an asymmetric bow shock, as seen in numerical simulations.

According to the numerical simulations of shocks by Hollenbach & McKee (1989), we would expect the surface brightness of the [Fe II] emission to be $10^{-15}$–$10^{-17}$ W m$^{-2}$ arcsec$^{-2}$ for a shock with a shock velocity of $70$–$150$ km s$^{-1}$ and a preshock hydrogen number density of $10^5$ cm$^{-3}$. In contrast, the peak brightnesses measured for the jet knots reach up to $10^{-15}$ W m$^{-2}$ arcsec$^{-2}$, $100$–$1000$ times as large as the modeled values. Such brightnesses, which are significantly larger than the shock models, could be explained if the hydrogen number density were to be higher (up to $10^6$–$10^7$ cm$^{-3}$) or a single knot were to contain multiple unresolved shock layers. The former explanation is consistent with our measurements of the electron densities (up to $\sim 10^4$ cm$^{-3}$), should the ionization fraction be low (0.01–0.1), as predicted for the “recombination plateau” in the postshock region, which is primarily responsible for low-ionization forbidden lines such as [Fe II], [O I], and [S II] at $\sim 10^4$ K (e.g., Hollenbach & McKee 1989; Hartigan et al. 1994).

The different peak intensities between the knots (Figures 6 and 7; Section 4.3) could be attributed to different column densities, electron densities, shock velocities, and filling factors. In Section 4.3 and Figure 7, we also show different

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**Table 8**

| Star | Year | Line$^a$ | Instrument | Instrument Resolution (km s$^{-1}$) | $V_{rad}$ (km s$^{-1}$) | Reference$^b$ |
|------|------|---------|------------|-------------------------------------|------------------------|-------------|
| RW Aur A | 2000 | [S II],[O I] | HST-STIS | 65 | 100 to 140 | 1 |
|       | 2001 | [Fe II] | Subaru-IRCS | 60 | 100 to 140 | 2 |
|       | 2002 | [O I] | HST-STIS | 65 | 100 | 3 |
|       | 2012–2021 | [Fe II] | Gemini-NIFS | 55 | 70 to 130 | This work |
| RY Tau | 2002 | [O I] | CFHT-OASIS | 135 | $-60$ | 4 |
|       | 2009 | [Fe II] | Gemini-NIFS | 55 | $-70$ to $-80$ | 5 |
|       | 2012–2021 | [Fe II] | Gemini-NIFS | 55 | $-70$ to $-120$ | This work |
| DG Tau | 1998 | [O I] | CFHT-OASIS | 90 | $-350$ to $-280$ | 6 |
|       | 1999 | [S II],[O I] | HST-STIS | 65 | $-250$ to $-350$ | 7 |
|       | 2001 | [Fe II] | Subaru-IRCS | 30 | $-200$ to $-250$ | 8 |
|       | 2003 | [O I] | HST-STIS | 65 | $-180$ | 9 |
|       | 2005 | [Fe II] | VLT-SINFONI | 100 | $-200$ | 10 |
|       | 2005–2009 | [Fe II] | Gemini-NIFS | 55 | $-170$ to $-250$ | 11 |
|       | 2013–2019 | [Fe II] | Gemini-NIFS | 55 | $-120$ to $-160$ | This work |

Notes.

$^a$ [Fe II] 1.644 μm, [S II] 6731 Å, and [O I] 6300/6363 Å.

$^b$ (1) Woitats et al. (2002), Melnikov et al. (2009), and Liu & Shang (2012); (2) Pyo et al. (2006); (3) Coffey et al. (2004); (4) Agra-Amboage et al. (2009); (5) Coffey et al. (2015); (6) Lavallee-Fouquet et al. (2000); (7) Liu et al. (2016); (8) Pyo et al. (2003); (9) Coffey et al. (2007); (10) Agra-Amboage et al. (2011); and (11) White et al. (2014b).
decay timescales for the [Fe II] intensity. We discuss the implications for this trend in the case where the emission is associated with shocks below.

Numerical simulations by Hartigan et al. (1994) have shown that the optical [S II] lines, with excitation conditions that are similar to those of the NIR [Fe II] lines (e.g., Hartigan et al. 2004b), have a decay timescale of ~240 days (see Equation (1) for the definition) for a shock velocity of 70 km s$^{-1}$, a preshock hydrogen number density of $10^3$ cm$^{-3}$, and an initial magnetic field $B_0 = 100 \mu$G. In practice, the actual shock velocities in our target jets may be significantly larger than 70 km s$^{-1}$, considering the measured jet velocities of 140–270 km s$^{-1}$ (Section 4.4, after correcting for jet inclinations). The decay timescales of the emission lines could be even smaller in such conditions, as such shocks yield higher electron densities, due to higher temperatures, leading to more rapid cooling (Hartigan et al. 1994). As shown in Figure 8, the observed decay timescale of the [Fe II] 1.644 $\mu$m emission is longer than these values. This is because, as the shock waves move away, they interact and heat new gas in the downstream.

Considering that the jet knot velocities do not change significantly for different epochs (see Tables 4–6), one would attribute the complicated time variations of the peak intensities in Figure 7 to different preshock conditions. The jet knots appear to spatially expand with time across the jet axis (Figures 9), and also, in some cases, along the jet axis (Figures 5). One would therefore expect the gas density in the jet knot to become lower with time, and, as a result, the intensity to become lower, as predicted by the shock models (Hollenbach & McKee 1989; Hartigan et al. 2004b). Such a trend for electron densities is qualitatively seen for some knots in Figure 7.

Could the shock velocity possibility be significantly smaller than that of the measured jet velocity? This would occur if the preshock gas were moving forward as well (e.g., Hartigan et al. 1987). Agru-Ambouge et al. (2009) estimated a shock velocity of ~20 km s$^{-1}$, based on their observations of the optical [O I] line and the absence of the optical [N II] line. However, a slower shock velocity would cause the decay timescale for the [Fe II] emission to be significantly longer than the observations: using the models for the [S II] line above, one would derive a decay timescale of ~4000 days for a shock with a shock velocity of 35 km s$^{-1}$. Detailed modeling of the [Fe II] emission for higher electron densities would allow us to discuss this issue further.

5.1.3. Other Possible Heating/Cooling Mechanisms

As described above, the observed trends for the jet knots could be explained with shock heating and cooling. The major reservation relating to the shock heating and cooling scenario is that we have not been able to spatially resolve the shock structures in the individual knots in our [Fe II] images close to the star.

The observed chains of spatially resolved knots may alternatively be due to nonuniform distributions of density or temperature without shocks (e.g., Shang et al. 2002, 2010; Liu & Shang 2012). This explanation may encounter the same problem of a short cooling timescale, as we discussed for the shocks described above. In other words, we need a heating mechanism to make the timescale of the intensity decay longer, as observed. Such heating could result from MHD waves (Shang et al. 2002; Skinner et al. 2011; Skinner & Güdel 2014) or from the dissipation of the turbulence in the jet (Shang et al. 2002). Shang et al. (2002) have also discussed heating with ambipolar diffusion, but they found that it is more effective in the outer regions of the jet (beyond 500–1000 au, corresponding to >3″ from our target stars).

In addition to the above mechanisms, X-ray radiation from the star, or from shocks close to the star, may also contribute to jet heating (e.g., Shang et al. 2002; Skinner et al. 2018). This heating mechanism should be more efficient closer to the star. It would therefore yield a longer decay timescale for a line intensity closer to the star. However, our observations do not clearly show such a trend (Figure 6). As the gas densities also affect the cooling timescales, better observations of the electron densities will be necessary to further investigate the feasibility of this scenario.

5.1.4. Possible Physical Link with Time-variable Mass Accretion

According to the moving knot scenario, the knots that we observed were ejected from the star at irregular intervals, for both RW Aur A (300–2000 days) and RY Tau (300–1200 days; Section 4.1). In the case of RW Aur A, Takami et al. (2020) have revealed a possible time correlation between these knot ejections and optical photometry+spectroscopy, perhaps due to a physical link between the jet ejections and mass accretion, as summarized in Section 1. For the jet from DG Tau, the measurements of the time intervals are still tentative, but those for knots C–D and D–E are 1300–1500 days, perhaps far less irregular than those for the other stars.

This possible discrepancy between DG Tau and the other stars may also be related to mass accretion. Both RW Aur A and RY Tau are known to show complicated variabilities in their profiles of optical permitted lines, which are probably signatures of mass accretion (Calvet et al. 2000; Najita et al. 2000), even over a few month scale (e.g., Petrov et al. 1999, 2001a; Alencar et al. 2005; Facchini et al. 2016; Takami et al. 2016, 2020). In contrast, Chou et al. (2013) conducted multi-epoch observations for these line profiles for DG Tau in 2010, as well as for the other stars, and found that the line profiles observed toward DG Tau were stable during the period of their observations. Thorough comparisons between the jet ejections and optical photometry+spectroscopy, like those made by Takami et al. (2020) for RW Aur A, will be necessary for the other stars as well, to further investigate this link.

5.2. A Search for Stationary Shocks

X-ray observations of the jets from some protostars and young stars indicate the presence of an inner stationary component, in addition to outer components with proper motions (e.g., Schneider & Schmitt 2008; Schneider et al. 2011). Such jets include one that is associated with DG Tau. Multi-epoch observations of the X-ray emission and NIR [Fe II] emission for this star show a stationary component at ~0′′/2 from the star (Güdel et al. 2011; White et al. 2014b). Gunther et al. (2014) conducted model calculations and demonstrated that such shocks could occur due to the recollimation process of the jet near its base.

Figure 11 shows the velocity-integrated maps for the bases of the three jets, without positional offsets. The green boxes show the possible stationary shocks. It is difficult to investigate the presence or absence of stationary shocks within ≤0′′/2 of the star, due to the imperfect subtraction of the bright
continuum. Observations at better angular resolutions and inner working angles will be necessary to confirm or reject this possibility.

6. Summary and Conclusions

We have conducted multi-epoch integral field spectroscopy ($R = 3000$–5500, $\Delta v = 55$–100 km s$^{-1}$) of the NIR [Fe II] emissions that are associated with well-studied jets from three active T Tauri stars: RW Aur A, RY Tau, and DG Tau. The observations were made using Gemini-NIFS, VLT-SINFONI, and Keck-OSIRIS, with a $\sim 0.1$ resolution. During the observations, from 2012 to 2021, we primarily covered the redshifted jet from RW Aur A and the Blueshifted jets from RY Tau and DG Tau, investigating the long-term time variabilities in detail.

Within 3$''$ of these stars, we identify a number of knots in the 1.644 $\mu$m emission—the brightest jet emission line in the spectral coverage of our observations. Most of these, if not all, appear to move outward, with proper motions of $0.1$–0.4, corresponding to tangential velocities of 70–230 km s$^{-1}$. During our observations, the jet ejections from RW Aur A and RY Tau were irregular, with time intervals of 300–2000 days. Our data for DG Tau are not sufficient to investigate such a trend, but the measured interval of 1300–1500 days is different from those that have been measured in the past ($\sim 900$ and $\sim 1800$ days between 1980 and 2005), which is indicative of an irregularity on a longer timescale.

To investigate the potential variabilities of mass accretion or stellar activities over a period up to $\sim 200$ yr, we performed comparisons between the measured tangential and radial velocities and those in the literature. For the DG Tau jet, both the tangential ($V_{\text{tan}}$) and radial velocities ($V_{\text{rad}}$) seem to have decreased over the past 10–15 yr: $V_{\text{tan}}$ from 100–200 to 70–90 km s$^{-1}$ and $V_{\text{rad}}$ from 170–350 to 120–160 km s$^{-1}$. In contrast, we do not find any clear evidence for time variations longer than those in our observations over 9 yr ($V_{\text{tan}}$ of 120–210 and 120–240 km s$^{-1}$ for RW Aur A and RY Tau, respectively).

The sizes of the individual knots appear to increase with time across the jet axis, and in some cases along the jet axis as well. In turn, their peak brightnesses in the 1.644 $\mu$m emission decrease by up to a factor of $\sim 30$ over the epochs of our observations. The decay timescale of the emission varies between the knots, and even in the same knot over different epochs, typically ranging between 300 and 3600 days, with a median value of $\sim 1000$ days. The complexity of the time variations can be explained if the jet knots are unresolved shocks, with the preshock density decreasing toward the downstream, but also with some additional spatial variation of the preshock density/temperature.

While the overall observed trends for the moving knots are consistent with the shock heating+cooling scenario, our data do not exclude the possibility that the knots are due to
nonuniform density/temperature distributions with another heating mechanism, such as energy transfer via MHD waves or turbulent dissipation. Furthermore, some of the identified knotty structures may be due to stationary shocks (i.e., without proper motions) that are associated with the base of the jet. Spatially resolved observations of these knots with significantly higher angular resolutions will be necessary to understand their physical nature.

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**Software:** IRAF (Tody 1986, 1993), PyRAF (Science Software Branch at STScI 2012), numpy (Oliphant 2006), scipy (Virtanen et al. 2020), astropy (Astropy Collaboration et al. 2013), Gemini IRAF package (Turner et al. 2006), ESO Refrex (Freudling et al. 2013), OSIRIS pipeline (Lyke et al. 2017; Lockhart et al. 2019).

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