THE 2008 OUTBURST IN THE YOUNG STELLAR SYSTEM Z CMa: THE FIRST DETECTION OF TWIN JETS

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ABSTRACT

The Z CMa binary is understood to undergo both FU Orionis (FUOR) and EX Orions (EXOR) type outbursts. While the SE component has been spectroscopically classified as an FUOR, the NW component, a Herbig Be star, is the source of the EXOR outbursts. The system has been identified as the source of a large outflow; however, previous studies have failed to identify the driver. Here, we present adaptive optics assisted [Fe II] spectro-images which reveal for the first time the presence of two small-scale jets. Observations made using OSIRIS at the Keck Observatory show the Herbig Be star to be the source of the parsec-scale outflow, which within 2′′ of the source shows signs of wiggling and the FUOR to be driving a ∼0.4 jet. The wiggling of the Herbig Be star’s jet is evidence for an additional companion which could in fact be generating the EXOR outbursts, the last of which began in 2008. Indeed, the dynamical scale of the wiggling corresponds to a timescale of 4–8 years which is in agreement with the timescale of these outbursts. The spectro-images also show a bow-shock-shaped feature and possible associated knots. The origin of this structure is as of yet unclear. Finally, interesting low velocity structure is also observed. One possibility is that it originates in a wide-angle outflow launched from a circumbinary disk.

Key words: binaries – ISM: jets and outflows – stars: formation

Online-only material: color figures

1. INTRODUCTION

Z CMa is a unique pre-main sequence binary (d ∼1150 pc) whose behavior, over the last two decades, has captured the interest of astronomers studying outburst activity in young stars (van den Ancker et al. 2004; Szeifert et al. 2010). The binary is known to consist of a Herbig Be star (NW component) and a FU Orionis star (FUOR; SE component) with the binary position angle (P.A.) constrained at ∼130° and separation at ∼8.1 (Barth et al. 1994). The classification of the SE component as a FUOR is based on its optical and infrared (IR) spectra which exhibit features associated with FUOR objects (Hartmann et al. 1989; Hartmann & Kenyon 1996). For example, in the optical the Balmer lines are found to have absorption features which are broad and blueshifted by a few hundreds of km s−1. The Na I lines also show deep absorption features and in the IR strong CO absorption at 2.2 μm is detected (M. Bonnefoy et al. 2010, unpublished). In addition to the recognized FUOR activity, Z CMa also undergoes EX Orionis (EXOR)-like outbursts, the source of which has recently been confirmed to be the Herbig Be star (Szeifert et al. 2010). EXORs are a class of eruptive variables, named after their class progenitor, EX Lupi, and because they were originally believed to mimic FUORs (Herbig 1989). In the case of Z CMa, these ∼1m–2m outbursts have typically occurred with a period of ∼5–10 years with recent events recorded in 1987, 2000, 2004, and 2008 (van den Ancker et al. 2004; Grankin & Artemenko 2009).

Studies have also revealed rich outflow activity in the vicinity of Z CMa. Poetzel et al. (1989) presented the first observations of the large-scale (∼3.9 pc, P.A. = 240°) optical outflow. They also noted that the optical forbidden emission lines (FELs) tracing the jet close to the source had unusual multiple component profiles. In total, they observe four distinct components within 12′′ of the central stars: a component at ∼−600 km s−1 which extends to 2′′, a component at ∼−500 km s−1 which extends to 12′′, a component at ∼−400 km s−1 which extends to 6′′, and a final low velocity component (<100 km s−1) which extends to 5′′. Subsequent studies of the Z CMa outflow have spanned a large range in wavelength from the radio to the X-ray regimes and differed on whether the FUOR or the Herbig Be star is driving the outflow. For example, Velázquez & Rodríguez (2001) presented radio observations of a thermal jet component to the Z CMa outflow. The jet had a P.A. of 245° in agreement with the Poetzel et al. (1989) observations and the authors argue that the FUOR is the driver of the jet. Garcia et al. (1999) published optical spectral images of the jet in the [O I]λ6300 line. They spatially associate the jet with the Herbig Be star rather than the FUOR; however, they also note the presence of the [O I]λ6300 line (an important jet tracer) in the spectrum of the FUOR. Stelzer et al. (2009) observed with Chandra an X-ray jet with a P.A. of 225° ± 5°. Since the beginning of the last outburst (2008 January) we have been leading a large observational campaign aimed at better understanding Z CMa and in particular the origin of the EXOR outbursts (Benisty et al. 2010; M. Bonnefoy et al. 2010, unpublished). An important aspect of this work is the observations focused probing the outflow activity and its relationship if any to the outburst activity. In this Letter, we present remarkable new observations revealing the presence of
two jets driven by the Z CMa system. What is clear from these observations is that the Herbig Be star is the driver of the parsec-scale outflow (P.A. = 245°) and that the FUOR is driving a 0′/4 micro-jet at a P.A. of ∼235°.

2. OBSERVATIONS AND DATA REDUCTION

The multiple component FEL profiles observed by Poetzel et al. (1989) combined with the subsequent conflicting detections of the Z CMa jet strongly suggested to us the presence of more than one jet launched from within the Z CMa system. With this in mind, we used the OH-Suppressing Infra-Red Imaging Spectrograph (“OSIRIS”) to investigate the two jets theory. OSIRIS is an integral field spectrometer (IFS) designed to work with the laser guide star and adaptive optic (AO) system on the W.M. Keck II telescope (Wizinowich et al. 2006). It is a lenslet-based IFS which provides a spectral resolution of 3800 (∼80 km s⁻¹) from 1–2.5 μm and offers a range of narrow and broadband filters of varying pixel scales and hence fields of view (FOV; Larkin et al. 2003). The observations were taken on the night of 2009 December 22 and in all cases the long axis of the detector was set at a P.A. of 230°. The AO system was used in Natural Guide Star mode with Z CMa itself as the guide star. As we wished to focus on observing the Z CMa [Fe II] 1.257 μm and 1.644 μm jet emission we used the Jbb (1.18–1.416 μm), Hbb (1.47–1.8 μm), Jn2 (1.23–1.29 μm), and Hn3 (1.59–1.68 μm) filters. The Jbb and Hbb were chosen with the 20 mas pixel scale and the Jn2 and Hn3 with the 35 mas scale. The data were reduced using the OSIRIS data reduction pipeline which provides for the sky-subtraction, correction of various artifacts and the extraction of the individual spectra into a data cube. The cosmic-ray correction, continuum subtraction, and mosaicking steps were done using specifically designed IDL routines. For further details on these procedures please refer to Agra-Amboage et al. (2009). Also note that the data have not been flux calibrated at this stage. As the Hbb and Jn2 observations were found to be of lower signal-to-noise ratio (S/N) we present here the Jbb and Hn3 results. The FOV of the individual Jbb and Hn3 observations was 0′.32 × 1′.28 and 1′.68 × 2′.24, respectively. However, as the source was positioned differently in each observation the mosaicing process increased the respective FOVs to approximately 0′.6 × 1′.6 and 2′.4 × 3′.4.

Figure 1. Continuum-subtracted velocity channel maps of the Z CMa [Fe II] 1.257 μm jet emission with the dashed lines delineating the P.A. of the jet structures. Contour levels start at 1%–2% of the maximum and increase by factors of √2. The emission below S/N = 3 is masked. Jet A (P.A. ~ 245°) is revealed, the origin of which is the Herbig Be star (H). This jet shows signs of possible precession (also see Figures 2 and 3) which explains why the chosen P.A. does not correspond exactly to the jet axis (on the smallest scales). A lower velocity jet, Jet B at a P.A. of ~ 235° is also seen. This jet extends to ~0′.4 and is clearly driven by the FUOR (F). Note the position of knot K1 and the lower velocity emission associated with both jets. Panel (f) is a channel map extracted from an SINFONI observation obtained in 2008 December. Due to the smaller pixel scale and shorter integration time only Jet B was detected. It is included here as it confirms that the FUOR is the driver of Jet B. K1 is also detected in the SINFONI data. Two jets driven by the Z CMa system. What is clear from these observations is that the Herbig Be star is the driver of the parsec-scale outflow (P.A. = 245°) and that the FUOR is driving a 0′/4 micro-jet at a P.A. of ∼235°.
Figure 2. Continuum-subtracted velocity channel maps of the Z CMa [Fe ii] 1.644 μm jet emission with the dashed lines delineating the P.A. of the jets. The extracted images are displayed on the top with the highest data values shown in yellow and the lowest in black. Jet A extends to ∼1″ with the addition of knot K2. The wiggling of Jet A is very clear. A third knot K3 and a bow-shock-shaped feature B1 are identified. Note the emission linking both K2 and K3 to the inner portion of Jet A (shown in Figure 4(b)). To highlight the complicated structure (e.g., the wiggling in Jet A), the corresponding contour plots are displayed on the bottom. Again the contour levels start at 1%–2% of the maximum and increase by factors of √2 and the emission below S/N = 3 is masked.

(A color version of this figure is available in the online journal.)

The seeing varied between 0.′75 and 0.′9 and the angular resolution achieved was 0.′05 for the Jbb observation and 0.′07 for the Hn3. Images obtained with the Suprime-Cam on the Subaru telescope and the SINFONI IFS are presented in Figures 2 and 3, respectively, as a support to the OSIRIS results.

3. RESULTS AND DISCUSSION

While the presence of two jets is immediately apparent from Figure 1 what is also evident is the rich and complex nature of the outflow activity in the vicinity of Z CMa. Hence, we shall use the channel maps and position–velocity (P–V) diagrams shown in Figures 1–4 to unravel and explore the origin of the different jet features. In all figures, the contour levels start at 1%–2% of the maximum and increase by factors of √2. For the channel maps, the velocity intervals are chosen to highlight the main features. The P–V diagrams were generated with a pseudo-slit of 0.′1 (Jbb) to 0.′14 (Hn3) in width. All velocities are with respect to the stellar velocity taken at +30 km s$^{-1}$ (heliocentric). Below each set of structures are divided into Jet A, Jet B, and a low velocity outflow and discussed separately.

3.1. Jet A: A Precessing Jet Driven by the Herbig Be Star

Jet A driven by the Herbig Be star is revealed in Figure 1(b) at a P.A. of ∼245°. The velocity and the P.A. of this jet approximately agree with what was imaged on the large scale by Poetzel et al. (1989), hence what is detected here is the
sub-arcsecond initial section of the parsec-scale outflow. In Figure 2(b), the jet is imaged on slightly larger scales and now extends to $\sim 1''$ with the addition of knot $K2$. Although $K2$ is detected at a lower velocity, we are confident that it is associated with the Herbig Be star jet as it lies along the same P.A. and is connected to the smaller scale jet by extended emission along the jet channel. From the P–V diagram (Figures 4(a) and (b)), the spread in jet velocities is $\sim 200$ km s$^{-1}$. The most important feature of this jet is that it appears to be “wiggling.” This is especially clear in Figure 3(a), where the image has been rotated so that the $x$-axis lies along the P.A. of Jet A. This behavior extends to larger scales as seen in Figure 3(b). Figure 3(b) is a section of an $H\alpha$ image taken with Suprime-Cam on the Subaru telescope. The positions of knots 1–4 which correspond to the $\sim 30''$ jet first detected by Poetzel et al. (1989) are slightly shifted to either side of the jet axis (by $\lesssim 1''$) offering further evidence of wiggling.

Jet precession is one possible explanation for jet wiggling (Bally & Devine 1994; Chandler et al. 2005). One theory of jet precession considers a protostellar disk in a binary system where the disk is misaligned with the orbital plane of the binary. The tidal interaction between the disk and the companion causes the disk to precess which in turn causes precession in any jet launched from the inner regions of the disk (Terquem et al. 1999). Alternatively, the wiggling could result if the jet source is in orbital motion around a close companion (Anglada et al. 2007). Either way the observed wiggling in Jet A offers strong evidence for an additional companion to the Herbig Be star. Accretion variability in young stars while not precisely understood is generally attributed to an instability in the accretion disk which can be caused by the presence of a companion (Forgan & Rice 2010). The typical size scale of the observed wiggling is $\sim 0.8$ which for a jet with a velocity in the range 500–1000 km s$^{-1}$ corresponds to a timescale of 4–8 years. This timescale is in agreement with the timescale of the EXOR outbursts, hence a previously undetected companion to the Herbig Be star could explain the EXOR outbursts.

Finally, we consider here the structures labeled as knot $K3$ and a bow-shock-shaped feature $B1$ (Figures 2(a) and (b)). The origin of $K3$ is very uncertain. While it does align with Jet A and while the P–V diagram shown in Figure 4(b) shows emission linking knots $K3$ to $K2$, the close proximity of $K3$ to $K2$ is confusing and raises questions over whether it is in fact part of Jet A. Additionally, the source of $B1$ is unclear. It is described here as being bow-shock shaped yet whether it is or not in fact a bow-shock needs to be confirmed through further observations. Also note that $K3$ is coincident with the triangular-shaped $B1$ the apex of which points into the Z CMa system. We offer two suggestions for the origin of these features. First, $B1$ could be a shock-excited cavity where oblique shocks along the cavity walls combine to give its triangular shape with $K3$ being part of the Herbig Be star’s flow. Alternatively, $B1$ could in fact be a bow-shock which is part of a third jet driven by a nearby source.
3.2. Jet B: A Collimated Micro-jet Launched by the FUOR

In Figure 1(c), the [Fe II] 1.257 μm emission associated with Jet B is shown. The direction of the jet points to the position of the FUOR and therefore is clearly driven by this star. Also the jet is seen in the P–V diagram Figure 4(a) and has a velocity spread of ∼150 km s$^{-1}$. The P.A. of the FUOR jet agrees with the P.A. of the X-ray knot at 2″ (Stelzer et al. 2009) and with the bow-shock-shaped feature labeled D located at 60″ (Poetzel et al. 1989) thus offering evidence of much older ejection events connected with the FUOR. Note that Jet B curves sharply at the end. This morphology is curious and it appears to be caused by a mixing of the emission from Jet B and knot K1 (the origin of which is unclear). Figure 1(f) shows a channel map extracted from SINFONI 1.257 μm observations of Z CMa taken a year previous to the OSIRIS data (M. Bonnefoy et al. 2010, unpublished). While these observations were not optimized for the detection of jet emission the FUOR jet was observed. It is included here as the smaller pixel scale of the SINFONI observations (12.5 mas) means that the jet was traced closer to the FUOR position providing confirmation that it is indeed launched by the FUOR.

Much evidence has been previously presented suggesting that FUORs drive outflows and collimated jets. However, the observations presented here are the first which unequivocally identify an FUOR as the driver of a collimated jet. Difficulties with identifying FUOR outflows include uncertainties associated with the classification of the star as an FUOR and the identification of the driving source of the jet. As FUOR candidates are often embedded in reflection nebulae it can be difficult to say whether they or a perhaps unidentified close companion are the drivers of the observed jets. Our observations of Z CMa clearly illustrate that this is an important consideration. An example of another likely FUOR jets is the [S II] micro-jet associated with the probable FUOR PPS 13 (Aspin & Sandell 2001). Detailed studies of FUOR jets will uniquely allow the impact of very high accretion rates on jet properties to be explored. Current models predict scalings of jet parameters with mass accretion rate and accretion rates on jet properties to be explored. Current models will potentially tell us something about the magnetization of the FUOR disks (Donati et al. 2005).

3.3. Low Velocity Structure

Distinct low velocity emission associated with the two jets is also detected. This is especially clear in the P–V diagrams presented in Figure 4. In Figures 1(b) and (c), we see that the emission associated with Jet A persists down to a velocity of ∼100 km s$^{-1}$ and is broader at lower velocities. Also, Figure 1(c) reveals the broader slower emission associated with the FUOR jet. Classical T Tauri jets have been shown to have a nested structure with the fastest densest material located along the jet axis and surrounded by slower less collimated emission. This has been described as an “onion-like” kinematic structure (Bacciotti et al. 2000; Lavalley-Fouquet et al. 2000). A proper analysis of the density, temperature, and kinematics of these two jets is needed in order to confirm if this model can be applied here. In addition, an interesting low velocity feature is revealed in Figure 1(d). A wide outflow with a velocity close to 0 km s$^{-1}$ and a P.A. intermediate between that of Jet A and Jet B is detected. Also it appears to originate from a position somewhere between that of the FUOR and the Herbig Be star. This structure presents itself in the P–V diagrams as a distinct kinematical component and could be tracing a wide-angled flow launched from a circumbinary structure. Alternatively, it could represent an expanding cavity pushed by the two jets. Further observations are needed to properly investigate the source of this component.

4. SUMMARY AND FUTURE PLANS

The observations of the Z CMa system presented here clearly highlight the complex nature of the outflow activity. In this Letter, we have begun the process of unraveling this activity. First, we have confirmed the existence of jets driven by both the FUOR and the Herbig Be star thus resolving the ambiguity over the driving source of the Z CMa parsec-scale outflow. Most interestingly we have observed the Herbig Be star jet to be wiggling. This strongly supports the existence of a second companion to the Herbig Be star. The idea that this companion could account for the EXOR outbursts must be investigated further. Finally, we have demonstrated that FUOR can drive collimated jets and we are confident that future observations of this and other FUOR jets will provide important constraints to jet launching models. While these results provide new and significant information on the Z CMa system several questions remain, the most pressing being whether or not the implied third component to the system actually exists. In addition, further observational studies are planned in order to investigate the origin of the structures K1, K3, and B1. It is envisioned that proper motion estimates will be particularly useful here. Considering the distance to Z CMa (∼1150 pc) and the velocity of Jet A, we would expect new features to emerge with a proper motion of ∼0.1 pc per year. It would be also be interesting to observe over the next few years new ejection events which can be directly related to the last outburst. If emerging knots can be detected in Jet A this would absolutely tie this jet to the Herbig Be star and thus provide compelling evidence of the relationship between outflow and accretion activity. Finally, a detailed study of the properties of Jets A and B (e.g., electron density, mass outflow rate) is currently underway and will be presented in a forthcoming paper. This will allow for comparison with leading jet launching models.

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