DISCOVERY OF A NEAR-INFRARED JETLIKE FEATURE IN THE Z CANIS MAJORIS SYSTEM

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ABSTRACT

We present near-infrared high-resolution observations of the young binary system Z Canis Majoris using the adaptive optics system at the Keck II telescope. Both components are unresolved at 1.25 and 1.65 μm, although high dynamic range images reveal a previously unknown jetlike feature in the circumstellar environment. We argue that this feature probably arises from light scattered off the walls of a jet-blown cavity, and proper-motion studies of this feature can probe the dynamics of the bipolar outflow. Potentially, the morphology of the dust-laden cavity walls offers a new probe of the momentum profile and collimation of bipolar winds from young stellar objects. We also derive high-precision binary parameters, which when combined with historical data have allowed the first detection of orbital motion. Finally, our observations confirm the high degree of flux variability in the system; the northwest binary component is dominant at the H band, in contrast to all previous observations.

Subject headings: infrared: stars — instrumentation: adaptive optics — planetary systems: protoplanetary disks — stars: formation — techniques: high angular resolution

On-line material: color figures

1. INTRODUCTION

Z Canis Majoris (Z CMa) is a luminous and irregularly variable young stellar object (YSO) originally classified as a Herbig Ae/Be star (HαBe, intermediate- to high-mass pre–main-sequence stars) on the basis of its emission-line spectrum and association with reflection nebulosity (Herbig 1960). It underwent an outburst lasting a few months in 1987, during which its spectral characteristics drastically changed and its visual brightness increased by a modest ~0.7 mag (Hessman et al. 1991). High-resolution optical and near-infrared (near-IR) spectra in the postoutburst state showed features typical of the FU Orionis (FU Ori) class, believed to be disk objects undergoing a period of very active accretion (Hartmann et al. 1989). Under this interpretation, Z CMa is unique in that it is the YSO with the highest known accretion rate (~10⁻³ M☉ yr⁻¹). The ranges of visual and near-IR magnitudes of the unresolved system found in the literature are V = 11.20–8.80, J = 6.16–5.87, H = 5.09–4.70, and K = 3.4–4.2.

A companion was discovered in IR speckle observations by Koresko et al. (1991). The binary system had an angular separation of 0″1 and position angle P.A. = 120° (measured east from north), where the primary is defined to be the northwest component, which dominates the flux beyond 2.2 μm. Individual spectral energy distributions reconstructed from the spatially resolved photometry, combined with unresolved photometry at optical and far-IR wavelengths, revealed that the emission in both components is dominated by circumstellar material, i.e., there are no signs of stellar photospheres. The southeast component has been identified as the FU Ori object inferred by Hartmann et al. (1989), while the northwest component is most likely a HαBe star surrounded by an asymmetric dust envelope (e.g., García, Thiébaut, & Bacon 1999).

In the last few years, HαBe and FU Ori objects have also been resolved using the techniques of long-baseline interferometry and aperture masking at near-IR wavelengths (Malbet et al. 1998; Millan-Gabet et al. 1999; Akeson et al. 2000; Millan-Gabet, Schloerb, & Traub 2001; Tuthill, Monnier, & Danchi 2001; Danchi, Tuthill, & Monnier 2001). However, the interpretation of the interferometer data depends on important model assumptions, namely, the extent to which the measured visibilities are systematically reduced (which results in an overestimate of the size measured) by flux arising in a widely separated companion or scattered by distant dust.

The discovery reported here took place in the larger context of a program of adaptive optics (AO) observations of HαBe systems, aimed at providing these constraints by exploring the level of extended emission present at spatial scales intermediate between the very narrow interferometric beams and the large-scale nebulosity known to surround these systems.

2. OBSERVATIONS

We observed Z CMa on 2001 January 11, using the AO system at the Keck II telescope (Wizinowich et al. 2000). These observations were carried out using the slit viewing camera (SCAM) of the NIRC2 instrument (McLean et al. 2000) as the imaging science detector. In these observations, Z CMa itself—unresolved by the Shack-Hartmann sensor subapertures—was used as the source of visible photons for the AO wavefront sensor. In order to achieve the highest sensitivity to scattered emission from circumstellar material, we limited our observations to the shorter wavelength near-IR bands: J (N3 filter, λ = 1.143–1.375 μm) and H (N5 filter, λ = 1.413–1.808 μm).

Our observing procedure consisted of establishing the maximum integration time per frame that did not saturate the bright stellar core and co-adding 30 such frames. For all frames, the correlated double sampling (CDS) readout mode was used. In order to search for circumstellar emission beyond the normal field of view of the SCAM array in AO mode (4.3″ × 4.3″) and to improve the image quality—by removing the effect of the NIRC2 slit—we recorded four such images nodding the telescope around a square by offsets of 4.3″/2, which resulted...
in a total field of view in the combined image of 6'45 × 6'45. We also recorded J-band images in which the central core was allowed to saturate the detector, in order to further augment our sensitivity to faint extended emission.

The results presented here have been obtained from the AO-corrected images, after straightforward processing (i.e., no de-convolution has been applied) consisting of bad pixel removal, flat-field correction (using images of near-sunset sky), and sky background subtraction (using images obtained with a telescope offset of 60' from the target source).

As an indication of the seeing quality and performance of the AO system at the time of our Z CMa observations, the images of an unresolved calibrator star—HD 54335, chosen to also have similar visual and near-IR magnitude as Z CMa—were fitted with the sum of two Gaussians of different widths, representing the narrow core and wide halo into which partially corrected point-spread functions (PSF) can be approximately decomposed. Using the FWHM of the core component as a measure of effective seeing, we find on average 45 and 46 mas at the J and H bands, respectively, both close to the diffraction limit of the 10 m telescope (31 and 42 mas, respectively). For this analysis, as well as in the rest of the Letter, stellar images are fitted with subpixel resolution using two-dimensional pixelized Gaussians.

3. THE Z CMa BINARY

We first derive the basic parameters of the Z CMa binary from our images. A model consisting of two scaled and displaced Gaussians gives us the binary separation, P.A., and flux ratio. These parameters are derived for each of the N images in our dithering procedure, and the final value adopted is the mean of these independent measurements, with a statistical error given by their standard deviation.

The plate scale and orientation of the AO images were calibrated using observations of the quadruple system ξ Ursae Majoris (HD 98230) and its published orbital elements (Mason et al. 1995). Given that the published orbit applies to the “Aa” center of mass and “B” component (the “a” component was unresolved until recent unpublished Keck aperture masking observations in 2000 June by one of the authors, J. D. Monnier), we estimated the location of the former in our images using the published masses (Heintz 1967). Assigning 10% and 30% mass uncertainties to the “A” and “a” components, respectively, we obtain a plate scale of 17.32 ± 0.06 mas pixel−1 (1.9% different than the nominal value of 17 mas pixel−1) and a P.A. offset (calculated − nominal) of −12.18 ± 0.18.

These results are summarized in Table 1. In addition, our 1.25 and 1.65 μm measurements are consistent with both binary components being unresolved; that is, we find no evidence for the extended component reported by Malbet et al. (1993) at somewhat longer wavelengths (λ > 3.87 μm).

Figure 1 shows the history of measurements of the Z CMa orbital elements up to this work (Koresko et al. 1991; Haas et al. 1993; Barth, Weigelt, & Zinnecker 1994; Thiebaut et al. 1995), spanning a total of 11.2 yr, and linear fits to the data. While only a marginal change in the angular separation is detected (X_red = 0.3 for the linear fit, compared to 0.8 for the weighted mean), the P.A. has clearly increased over this period of time (X_red = 0.6 for the linear fit, compared to 5.8 for the weighted mean), making this the first detection of orbital motion in this system.

The linear fit to the P.A. data gives a total change of 8°8 ± 1°5. For a distance to Z CMa of about 1150 pc (Herbst, Racine, & Warner 1978), the ∼0′.1 angular separation corresponds to a projected linear separation of 115 AU. Assuming masses for the components of 1 and 5 M⊙, typical of T Tauri and HAeBe stars, respectively, the period of a face-on circular orbit would be ∼500 yr and the expected rate of P.A. change ∼0′′7 yr−1. Therefore, our detection of a 8°8 change in about a decade is indeed plausible.

Previous workers have found the near-IR flux ratios to be highly variable: (NW/SE) = 1.0–0.3, (NW/SE) = 0.2–0.5, and (NW/SE) = 1.6–3.3 (Koresko et al. 1991; Haas et al. 1993). As can be seen in Table 1, we find the unexpected result that the northwest (HAeBE) component becomes brighter than the southeast (FU Ori) component at the H band, in contrast to previous reports that the northwest component became the brightest in the system at the K band and longer wavelengths. This flux reversal could be naturally explained if the FU Ori object has been continuously fading following its recent outburst. Approximate absolute photometry may be derived from our observations as follows.

The total flux of the Z CMa system at our epoch is estimated using the calibrator (HD 54335) as a flux standard. Its Two Micron All Sky Survey (2MASS) fluxes are F_J (HD 54335) = 19 ± 4 Jy and F_H (HD 54335) = 31 ± 6 Jy. From our images we derive a ratio of fluxes between Z CMa and HD 54335 of 1.39 ± 0.08 and 2.68 ± 0.25 at the J and H bands, respectively. The resulting combined fluxes of Z CMa as well as those of its components, derived using our estimates of the sum and ratio of fluxes, are also given in Table 1. Indeed, these

| Filter | N | Flux Ratio (NW/SE) | Separation (arcsec) | P.A. (deg) | Total Flux (Jy) | Flux SE (Jy) | Flux NW (Jy) |
|--------|---|------------------|---------------------|-----------|----------------|-------------|-------------|
| J (N3) | 4 | 0.50 ± 0.05      | 0.109 ± 0.002       | 2.7 ± 0.6 | 1.8 ± 0.4      | 0.9 ± 0.2   |
| H (N5) | 3 | 1.18 ± 0.06      | 0.108 ± 0.002       | 7.9 ± 1.7 | 3.6 ± 0.8      | 4.3 ± 0.9   |

Figure 1.—Chronology of Z CMa binary separation measurements. We clearly detect a position angle increase of 8°8 ± 1°5 over 11.2 yr.
estimates clearly show that the FU Ori object has been dimming between 1986 and 2001. In particular, comparing with the epoch of the Koresko et al. (1991) observations, the southeast fluxes have decreased by $\sim 1.1 \pm 0.4$ and $\sim 0.7 \pm 0.3$ mag at the $J$ and $H$ bands, respectively. In contrast, the HAeBe photometry is consistent with no flux change at the $J$ band ($\Delta m_J \approx 0.1 \pm 0.5$) and a marginally significant increase at the $H$ band ($\Delta m_H \approx 0.5 \pm 0.4$).

4. HIGH DYNAMIC RANGE IMAGING: DISCOVERY OF A NEW JETLIKE FEATURE

4.1. Image Processing

We have detected a new jetlike feature in deep images at the $J$ band in which the stellar cores were saturated. Unfortunately, there are many imaging artifacts in such high dynamic range (DR) images, and we briefly mention the dominant ones before discussing the jetlike feature discovered around Z CMa. In Figure 2, we show the mosaicked images of Z CMa and the unresolved reference star (HD 54335), in which an azimuthally averaged PSF core has been subtracted to artificially enhance the DR in the image. We have marked the dominant artifacts common to both Z CMa and the reference star but note the interesting new feature not associated with the PSF. Prior to this detection, no extended structure was known for Z CMa at these wavelengths and scales (less than 1") beyond that of a pure binary (nebulosity on larger scales has been reported by Nakajima & Golimowski 1995).

Figure 3 shows a close-up of the region near the new narrow feature, rotated so that north is up and east is left. In order to remove the wings of the PSF, we have subtracted a two-component model of the binary star using the PSF measured with the reference star. Clearly, this subtraction is imperfect, as evidenced by the speckled residuals within 0.5 of the binary. Despite these obvious flaws, the DR in the image (unsaturated peak-to-noise ratio) is $\sim 200,000$ beyond $\sim 0.5$ from the central binary, and the signal-to-noise ratio in the jetlike feature is greater than 10. The jetlike feature extends to $\sim 0\farcs9$ (1135 AU) from the central binary in the south-southwest direction and has a width of $\sim 0\farcs1$ (115 AU).

4.2. Discussion

It is likely that the extended emission we have detected is stellar light or disk emission scattered off dust grains, since at the observed distance from the central stars this dust would be too cold to emit thermally in the near-IR. Alternatively, the emission could arise from a faint emission line within the $J$-band bandpass, a possibility that needs to be eliminated in follow-up observations. We note that the jetlike feature is not detected in our $H$-band images, likely a consequence of the lower DR in those images (with nonsaturated peaks) and/or the lower efficiency of scattering by dust at longer wavelengths.

Assuming scattering by dust, an intriguing interpretation is that this scattering takes place off the inner walls of an evacuated cavity carved by the well-known large-scale outflow. A
bipolar outflow was discovered by Poetzel, Mundt, & Ray (1989), traced by several Herbig-Haro objects (blue- and red-shifted sides) and a jet (blueshifted side, also southwest direction). The total extent of the outflow was 3.6 pc, oriented at P.A. = 60°. Garcia et al. (1999) reported an optical jet in [O i] extending approximately 1° from Z CMa at P.A. = 240°. The radio counterpart of the outflow was also detected in CO lines (Evans et al. 1994) and in the thermal jet (Velázquez & Rodríguez 2001), both oriented coincident with the optical jet. In the latter case, the high angular resolution of the Very Large Array (VLA) observations allowed for the first time to clearly identify the origin of the outflow with the southeast (FU Ori) binary component. Understanding the shape of the jet-blown cavity and the amount of swept-up dust could constrain the momentum profile of the bipolar winds, testing current theories for such winds and the generation of jets (e.g., Shang, Shu, & Glassgold 1998; Matzner & McKee 1999).

Figure 3 also indicates the direction of the previously known optical jet and bipolar outflow at P.A. = 240°. If the near-IR feature arises from light scattering off dust swept up into a thin shell surrounding a jet-blown cavity, we would expect features on either side of the jet direction (as is also indicated in Fig. 3) and both should be (more or less) static. However, we do not see any evidence for symmetrical emission on the other side of the optical jet, casting doubt on this hypothesis. On the other hand, the high level of spurious emission may be masking this feature, and even higher DR observations are needed before this interpretation can be ruled out.

Alternatively, the emission may be directly associated with a different or new jet, given its morphology and association with known accretion objects. If the feature is moving with typical jet velocities (e.g., 500 km s^{-1}; Poetzel et al. 1989), then proper motions of the jet feature of up to 100 AU yr^{-1} (∼90 mas yr^{-1}) are expected and should be readily detectable within a short time span, in contrast to the previous hypothesis.

Unfortunately, because of the PSF artifacts in these first images, the new feature cannot be followed close enough to the central binary to establish whether or not it is associated with one of the components, and a higher signal-to-noise ratio at close separations plus optimum placement of the feature with respect to the PSF artifacts may be able to resolve this issue.

5. CONCLUSIONS

We have detected a new jetlike feature in the close environment of the young stellar binary Z CMa. The feature extends about 1035 AU from the central binary, in the south-southwest direction, and has a width of about 115 AU. A symmetric feature to the other side of the known optical jet and bipolar outflow is expected but not detected, and therefore further targeted observations are required to establish whether this new feature is indeed associated with the bipolar outflow (e.g., scattering off dust in its inner walls) or constitutes an independent jet. Our high-resolution observations have also revealed for the first time orbital motion in the Z CMa system, as well as further established the high degree of flux variability of its individual components.

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