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Speckle masking observations of the young binary Z Canis Majoris*

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Abstract. We present the first speckle masking observations of the pre-main sequence binary system Z CMa at optical wavelengths (narrow-band R filter and edge filter RG 610). The diffraction-limited images confirm that Z CMa is a binary with a separation of 0.100″± 0.008″at position angle 305°± 2°. The intensity ratio of the stars is 7.2 for the narrow-band R filter and 7.7 for the RG 610 filter. The south-eastern component is the brighter component (i.e. the FU Ori object), in agreement with the results of Koresko et al. (1991) based on near-infrared speckle data. However, our optical detection of the north-western component (the infrared companion) would not have been expected according to Koresko et al.'s analysis. One possible explanation could be scattered light. This agrees with recent polarimetric evidence from Whitney et al. (1993) that scattering plays a role in seeing the infrared companion. We discuss the possibility that both components of the Z CMa system may be FU Ori objects.

Key words: stars: binaries: visual – stars: pre-main sequence – techniques: image processing – techniques: interferometric

1. Introduction

Z CMa is a famous member of the class of Herbig Ae/Be stars associated with nebulosity (Herbig 1960; The et al. 1993). It is located on the outer edge of a shell of gas swept up by a supernova remnant in the CMa OB1 association (Herbst & Assousa 1977; Herbig 1991). Possibly, the formation of Z CMa was triggered in this shell and, because the shell is decelerating, the young stellar object moved out of the shell. This theory leads to an estimate of the age of Z CMa of a few times 10^5 yr and explains the rather low value of visual extinction (A_V = 1.8, Hartmann et al. 1989). The distance to the CMa OB association is usually taken to be 1150 pc (Claria 1974), although more recent data suggest 930 ± 120 pc (Ibragimov & Shevchenko 1990). Therefore, we adopt here a distance to Z CMa of 1 kpc.

Z CMa is known to be an FU Ori type object based on its optical and near infrared spectrum (Hartmann et al. 1989). FU Ori objects (also called FUORs for short) are young stellar objects which are believed to go through sporadic bursts of disk accretion, the cause of which is unclear at present, but is probably related to an opacity-dependent inner disk instability (see, e.g., Clarke et al. 1991; Bell et al. 1991; Kawasoe & Mineshige 1993). These accretion events lead to huge brightness variations. In the case of Z CMa, the visual brightness varied by some 2.5 magnitudes in the 1920–1930s (Covino et al. 1984), and its current (1993) magnitude in the visual is around m_V = 10 (Miroshnichenko et al. 1993; Shevchenko priv. comm.), corresponding to an absolute magnitude M_V near 0. Most of the visible light is thought to be due to accretion luminosity generated on the surface of a "burning" inner accretion disk (Hartmann et al. 1989). Some mini-eruptions of the order of 0.2–0.3 magnitudes occurred during 1982 and 1989 over timescales of a few months (Hessman et al. 1991; see also Haas et al. 1993). The H_α line, which varies in strength, exhibits a P-Cygni profile, indicating a fast wind (of the order of 500 km/s, Hessman et al. 1991). A very prominent bipolar jet is also present (Poetzel et al. 1989) suggesting the presence of a disk to collimate the outflow.

More direct evidence for large amounts of cold disk material comes from the detection of dust continuum emission at 1.3 mm. The inferred mass of circumstellar gas and dust is of the order of 2 $M_\odot$ (Weintraub et al. 1989; Beckwith & Sargent 1991; Reipurth et al. 1993), assuming a dust opacity at 1.3 mm of 0.02 cm^2/g and an average dust temperature of 20–40 K. An interesting possibility to trigger repetitive FUOR-type enhanced accretion events would be the tidal interaction of the accretion disk with a close companion during repeated periastron passages (Bonnell & Bastien 1992).

Recently, infrared speckle observations have led to the discovery that Z CMa has an infrared companion at projected separation 0.10″(100 AU) and PA = 122° northwest of the optically bright component (Koresko et al. 1991; Haas et al. 1993; see also Leinert & Haas 1987 and Koresko et al. 1989). This companion dominates the luminosity of the system longward of 2 μm (Ko-

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* Based on observations collected at the European Southern Observatory, La Silla, Chile.

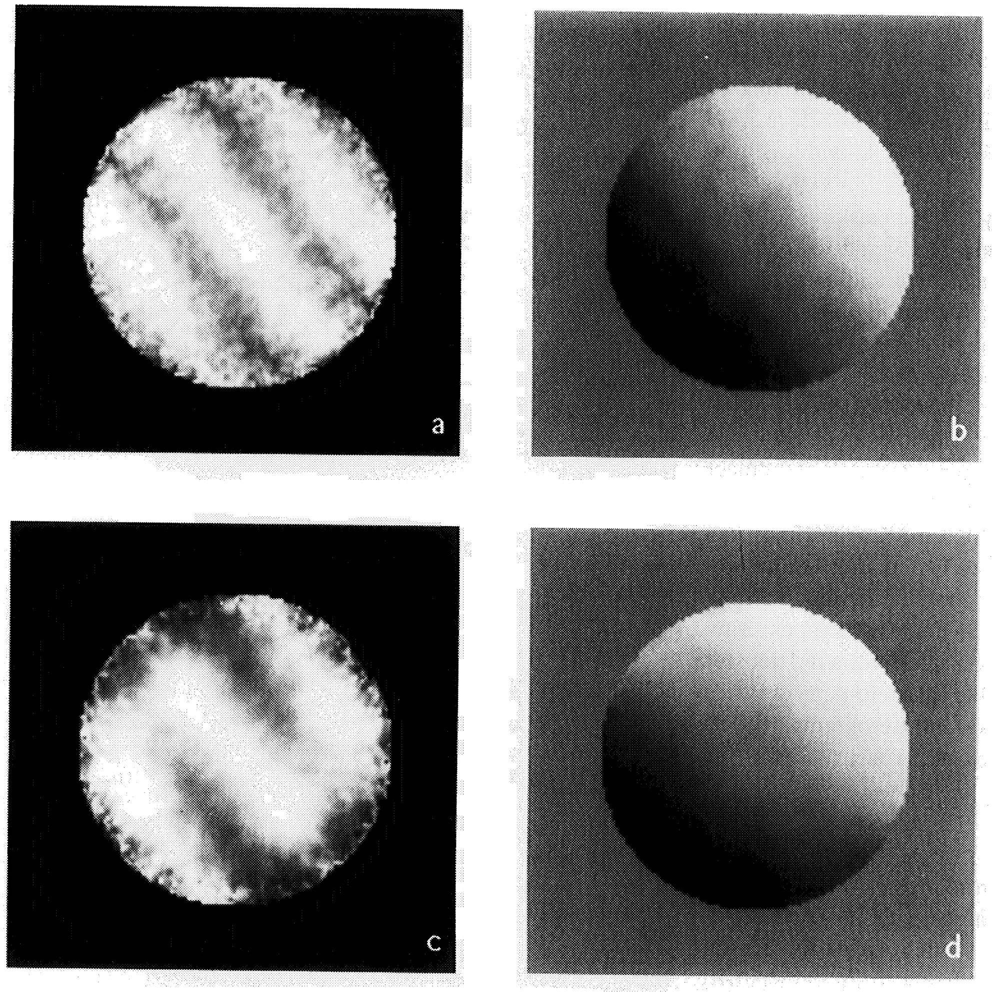

Fig. 1a–d. Reconstructed power spectra and Fourier phases of Z CMa: **a** narrow-band R power spectrum, **b** narrow-band R phase, **c** RG 610 power spectrum, **d** RG 610 phase.

resko et al. 1991), and it is therefore conceivable that most of the mm dust continuum radiation also comes from circumstellar matter associated with the infrared companion and not from the optically dominant component. This would imply a dust disk or dust shell around the infrared companion, in addition to the dust disk around the optical component. Koresko et al. (1991) made an attempt to decompose the spectral energy distribution associated with the two stellar components of the Z CMa system. They suggest that the bulk of the cold material is in the form of a *circumbinary* disk of dimension 500 AU which feeds the inner circumstellar accretion disk around the optical component. In this geometry the infrared companion does not have an accretion disk but is embedded in a thick dust shell (Koresko et al. 1991). Malbet et al. (1993) claimed to have detected Koresko et al.'s circumbinary disk in the Z CMa system at 3.9 μm using the ESO adaptive optics system, but more recent 2D speckle observations at 4.8 μm have not confirmed this claim (Tessier et al. 1993). It is clear that more data are required to clarify the geometry and evolutionary state of this complex system. Here we present speckle masking observations which resolve the Z CMa binary for the first time at optical wavelengths (i.e. the infrared companion is also detected in the visible!). The implications of this new result will be discussed.

2. Observations and data reduction

The Z CMa speckle interferograms were obtained with the 2.2 m ESO/MPG telescope at La Silla on March 28, 1993. The following four speckle data sets of Z CMa and of the reference star SAO 152332 were recorded through an interference filter with center wavelength/bandwidth of 6581 Å / 530 Å (henceforth narrow-band R filter) and through the Schott edge filter RG 610:

(1) Z CMa: filter 6581 Å / 530 Å (narrow-band R filter), 2500 frames
(2) Z CMa: filter RG 610, 2500 frames
(3) SAO 152332: filter 6581 Å / 530 Å, 1250 frames
(4) SAO 152332: filter RG 610, 1250 frames

The exposure time per frame was 50 ms. The field of view was about $6.2'' \times 6.2''$ (512×512 pixels). The image scale was $0.0123''$/pixel. Average seeing was $0.9''$. Note that the narrow-band R filter includes the H_α line, but the width of the filter is much larger than the H_α line width of Z CMa; therefore, this filter is essentially a continuum filter.

The speckle raw data were recorded with the speckle camera described by Baier & Weigelt (1983). The detector used for the Z CMa observations was an image intensifier with a gain of 500 000 coupled optically to a fast CCD camera (pixel rate 2

MByte/s, correlated double sampling). A new system of Digital Signal Processors was used for real-time speckle interferometry and for fast data storage simultaneously on 4 Exabyte streamers. The quantum efficiency of the image intensifier was 12% at 5000 Å, 8% at 6000 Å, 6% at 8000 Å, 4% at 8500 Å, and less than 1% at 9000 Å.

The speckle data were reduced by speckle masking (Weigelt 1977; Lohmann et al. 1983). The ensemble average bispectrum of the speckle interferograms was calculated with a resolution of 45^4 pixels. The 4-dimensional photon bias in the average bispectrum was compensated with the method described by Pehlemann et al. (1992). The average photon shape power spectrum and bispectrum, which are required for the photon bias compensation, were obtained by analysing flat-field frames. From the bias-compensated average bispectrum the phase of the object Fourier transform was reconstructed by phase recursion. For the recursion every pixel in the 4-dimensional bispectrum was weighted with its signal-to-noise ratio. The modulus of the object Fourier transform was derived from the ensemble average power spectrum of all speckle interferograms by compensating the photon bias terms and the speckle interferometry transfer function (Labeyrie 1970). The speckle interferometry transfer function was derived from the speckle interferograms of SAO 152332 observed after the observation of Z CMa.

3. Results

Figure 1a is the Z CMa power spectrum reconstructed from the narrow-band R data and Fig. 1b is the object Fourier phase reconstructed from the average narrow-band R bispectrum. Figure 1c shows the power spectrum reconstructed from the RG 610 speckle interferograms, Fig. 1d is the RG 610 Fourier phase. Figure 2a shows one of 2500 recorded speckle interferograms of Z CMa. Figures 2b and 2c are the high-resolution speckle masking images of Z CMa reconstructed from the narrow-band R and the RG 610 data, respectively. The resolution is diffraction-limited ($0.076''$). The separation of the two stars is $0.100'' \pm 0.008''$, the position angle is $305° \pm 2°$. The intensity ratios are 7.2 for the narrow-band R filter and 7.7 for the RG 610 filter.

Figure 3 shows contour plots of the two high-resolution reconstructions of Z CMa. Figure 3 illustrates that no extended halo or disk is visible in our optical reconstructions. The brightness level of the faintest contour line is about 0.002 of the peak brightness (brightest pixel in the image). Even at this low intensity level no asymmetric halo or disk is visible. The average brightness of the brightest peaks in the background intensity in the image (i.e., the upper limit for the brightness of an extended halo in the image with $\sim$ 0.1" resolution) is about 10% of the peak brightness of the fainter star.

4. Discussion

The most surprising result of our diffraction-limited optical observations of Z CMa is the fact that the infrared companion is detected at all. Judging from the proposed decomposition of the spectral energy distribution (SED) of the Z CMa system

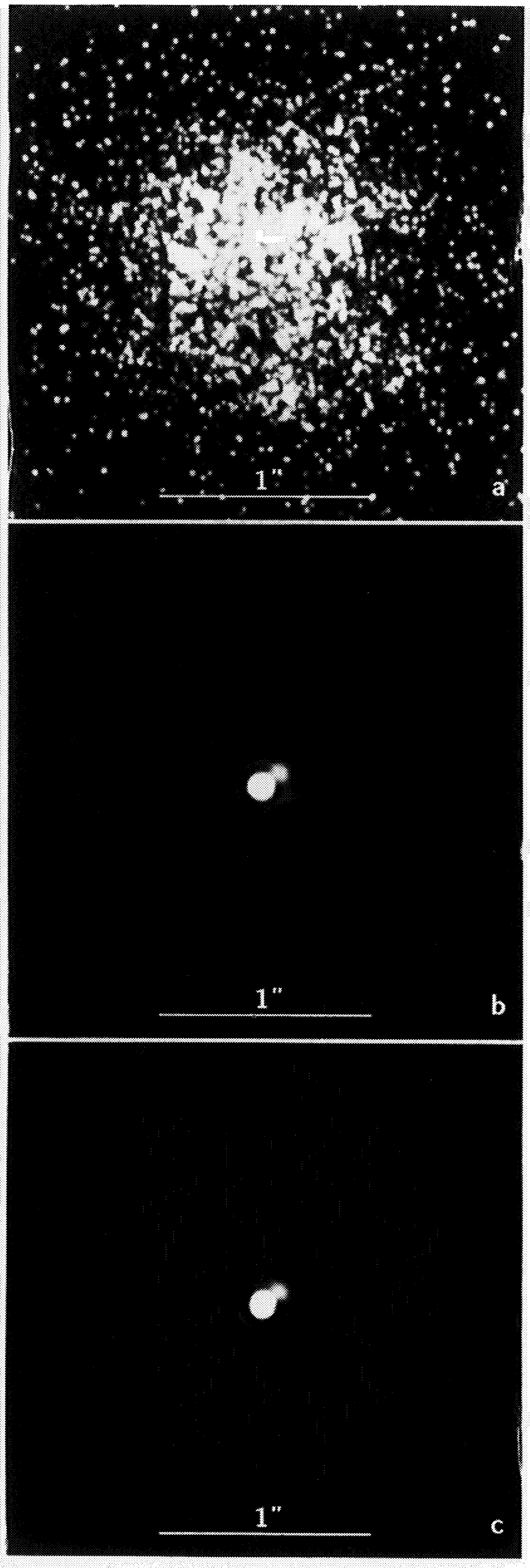

Fig. 2. a One of 2500 recorded speckle interferograms of Z CMa (200^2 pixel of the 512^2 frame). **b** High-resolution narrow-band R speckle masking reconstruction of Z CMa. **c** High-resolution RG 610 speckle masking reconstruction. North is up and east to the left

into the SEDs of the two individual components (Koresko et al. 1991, their Fig. 4), one would not have predicted the detection of the infrared companion (NW component) in the narrow-band R optical continuum. The continuum flux ratio of the Z CMa components at these wavelengths (near H_α) estimated from the above reference is of the order of 1000:1, while the observed one is about 7. As mentioned before, the bandwidth of the narrow-band R filter is sufficiently wide (530 Å) so that the observed flux ratio is essentially unaffected by the H_α line; the line is about 500 km/s (i.e. about 10 Å) wide and the line-to-continuum ratio is about 10:1 (Hessman et al. 1991; Finkenzeller & Mundt 1984). The independently observed flux ratio in the RG 610 filter is very similar to that in the narrow-band R filter, supporting the evidence that the narrow-band R filter flux ratio is indeed a continuum flux ratio. This is important, as it means that the infrared companion is not a pure emission line object.

We note that the RG 610 filter is open towards the red, so that its effective bandwidth is given by the declining quantum efficiency of the detector system. As the infrared companion has a SED that rises towards the red, one might have expected that the IR companion became relatively brighter in the RG 610 filter than in the narrow-band R filter. That this is not the case, can be understood in terms of loss of fringe contrast due to the smearing of speckles for such a broad filter as the RG 610 filter. Correspondingly, we have assigned a larger error bar to the flux ratio in the RG 610 filter than in the narrow-band R filter.

How the optical detection of the infrared companion can be interpreted depends on whether the visible light from the companion is direct light or scattered light. Direct light could be an explanation, provided that the extinction between the near-infrared and the visible is largely wavelength-independent (e.g., due to the growth of small grains). Such anomalous extinction is sometimes observed towards young stars (Elsässer et al. 1982, see also Martin & Whittet 1990). Scattered light is another explanation, especially in view of the recent polarimetric observations by Whitney et al. (1993). These authors discovered that the emission lines from the Z CMa system are surprisingly all highly polarized. They interpret the emission line spectrum as coming from the infrared companion, from which, at visual wavelengths, we receive only scattered light. This light may originally escape from the embedded young star and/or its inner accretion disk via a hollow cone, excavated by a bipolar outflow or jet, and may then be scattered into our line of sight (for supporting calculations, see the models of Whitney & Hartmann 1993). If the origin of the optical emission of the infrared companion is from a hot accretion disk, it may be generated by an *embedded* FUOR event, but is otherwise similar to the FUOR associated with the less obscured optical primary (Hartmann et al. 1989). This would be in line with the idea of Bonnell & Bastien (1992) where the two components of a binary system mutually trigger an accretion instability. Thus in Z CMa we might be dealing with a double FUOR, similar to the case of RNO 1 B and C (see Kenyon et al. 1993).

Furthermore, our detection rules out the possibility that the companion is located behind a perhaps extended accretion disk around the optical primary (SE component). This possibility,

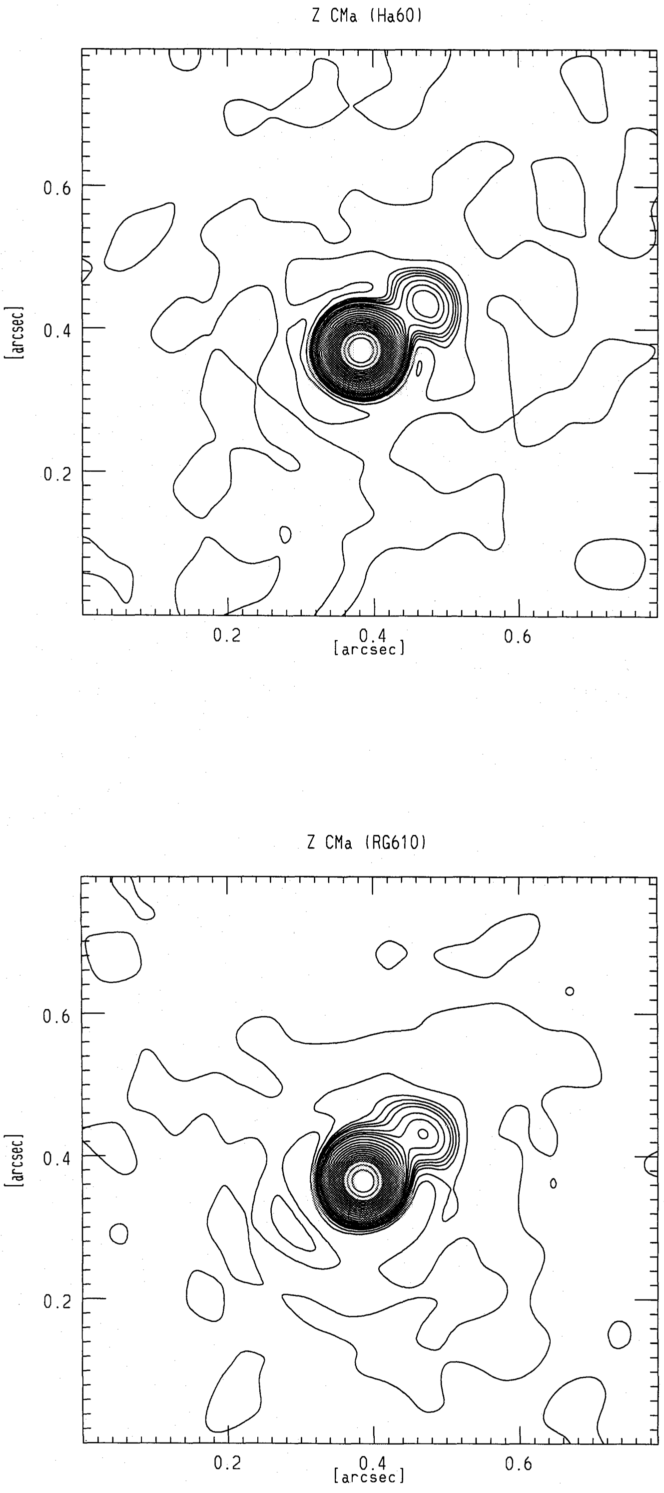

Fig. 3a and b. Contour plots of the speckle masking reconstructions of Z CMa shown in Figure 2 (**a** narrow-band R; **b** RG 610). The contour levels are 0.002, 0.02, 0.04, 0.05, 0.06, 0.07, 0.09, 0.11, 0.13, 0.16, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55, 0.60, 0.65, 0.70, 0.80, 0.90 of the peak brightness among others, has been mentioned to explain the existence of IR companions (Mathieu 1993).

Another useful result worth emphasizing, is the finding that the separation and position angle in the optical are almost exactly equal (in spite of the small separation) to those determined from the infrared speckle data. This suggests that we indeed see the same objects in the optical as in the infrared.

The results of the present speckle masking observations of Z CMa show the way to promising new speckle masking observations in the future:

Firstly, it seems possible to apply speckle spectroscopy (Weigelt 1981; Grieger et al. 1988) to the Z CMa binary system. Given that there is a jet-like outflow present in Z CMa (Poetzel et al. 1989) and a broad H_α emission with a P-Cygni profile (Finkenzeller & Mundt 1984; Hessman et al. 1991), we suspect that the outflow may be traced by the H_α emission (cf. Cabrit & Andre 1991). If we can resolve the Z CMa system in H_α, we may thus hope to discern from which component of the binary system the jet-like outflow originates. If in future observations the line emission is registered coming from both components, this could be taken as an indication that the system is indeed a double FUOR similar to RNO1B+C. We may also hope to detect *extended* H_α emission, i.e. to resolve the bright inner part of the jet/wind outflow. Such observations will benefit enormously from the VLT resolution.

Secondly, we should be able to determine separation and position angle of the binary with much improved accuracy (2 mas and 0.5°, respectively). This will allow us to study the orbital motion of the components. For example, the orbital period of the system is of the order of 1000 yr if the sum of the masses is near 1 $M_\odot$. If the system mass is closer to 10 $M_\odot$, the orbital period reduces to about 300 yr, implying a motion of 1°per year. This should be measurable.

Finally, Z CMa will be an interesting object for the VLTI. The diameter of the hot optical accretion disk is estimated to be 6 AU (Hartmann et al. 1989), i.e. 6 mas at the distance of Z CMa. Comparing this value with the spatial resolution of the VLTI (1 mas in the visible) demonstrates that we have reason to hope to resolve the accretion disk of the Z CMa FUOR with the VLTI. In fact, if the optical emission from the IR companion is also due to an accretion disk, we may be able to resolve it as well.

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