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The identification of the transient X-ray pulsar Cepheus X-4 with a Be/X-ray binary. ⋆

J.M. Bonnet-Bidaud[1] **and M. Mouchet**[2,3]

[1] Service d'Astrophysique, CEA, DSM/DAPNIA/SAp, CE-Saclay, F-91191 Gif sur Yvette Cedex, France
email:bobi@sapvxg.saclay.cea.fr
[2] DAEC, Observatoire de Paris, Section de Meudon, F-92195 Meudon Cedex, France, email:mouchet@obspm.fr
[3] Université Denis Diderot, 2 Place Jussieu, F-75005 Paris, France

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Abstract. We present long slit spectral (375-725 nm) observations of the proposed identification of the transient 66s X-ray pulsar Cep X-4=GS2138+56. Spectra show features typical of Be/X-ray binaries. Superimposed on a weak emission from the IC 1396 nebula, strong Hα (4.5 nm EW) and Hβ (0.3 nm EW) lines are seen in emission with the other Balmer lines in absorption. Significant interstellar absorption features are also detected, including a strong Na I doublet (589 nm) and diffuse bands at 443, 578 and 628 nm. From the shape of the continuum as well as the lines present in the spectrum, a most probable spectral type of B1-B2V is derived with a reddening of E_{B-V}=1.3±0.1. The reddening value is corroborated by the measure of interstellar absorption features, except for the sodium line which appears to be in excess and may be partly from circumstellar origin. The optical absorption is fully consistent with the column density derived from X-ray spectra, therefore confirming the identification. Despite apparent spatial coincidence, the source is located much further away than the local intervening nebula IC1396. The best estimate of the distance is D=(3.8±0.6) kpc, which places the source in the outer Perseus arm of the Galaxy. At this distance, the X-ray quiescent luminosity is (3-6) 10^{33} erg.s^{-1}, thus comparable to typical Be/X-ray binary low states.

Key words: X-rays: binaries, Stars: emission line Be, Stars: pulsars: individual: Cep X-4

1. Introduction

The X-ray source Cep X-4 was discovered in a transient high level X-ray flux in 1972 by the satellite OSO-7 (Ulmer et al. 1973). Early positions, accurate only to a fraction of degree, led to a suggested identification with the massive O6.5V star HD 206267, responsible for the excitation of the IC 1396 nebula (Liller 1974), though further observations did not confirm the identification (Hensberge & Hammerschlag 1975). The source was not detected again by an X-ray satellite till the observation of a new outburst by GINGA in April 1988. From these observations, coherent 66s pulsations were reported, revealing an X-ray pulsar with a complex X-ray spectrum, including a possible 30keV cyclotron absorption feature (Koyama et al. 1991, Mihara et al. 1991). The position of the pulsar Cep X-4/GS2138+56 was refined to a (15'x6') error box and, assuming circularity, Doppler changes of the X-ray pulses were used to constrain the orbit to a period more than 23 days, suggesting a massive X-ray binary. A new outburst, detected in 1993 by the ROSAT satellite during pointed observations and a residual faint emission when the source has declined by a factor more than 1000, were used to further refine the position (Schulz, Kahabka & Zinnecker 1995). An association with a m_V=14.2 Be star at α_{2000} = 21h39m30.6s and δ_{2000} = +56°59'12.9" was proposed by Roche, Green & Hoenig (1997) on the basis of the strong Hα emission (see also Argyle 1997). We presented here the first detailed spectroscopic information on this star, establishing the identification with a typical Be/X-ray binary. Preliminary results were given in Bonnet-Bidaud & Mouchet (1997).

2. Observations and results

Spectroscopic observations were conducted at the 1.93m telescope of the Haute-Provence Observatory (France), equipped with the Carelec spectrograph (Lemaitre et al. 1990), during two subsequent nights on July 29th and 30th, 1997. Series of (375-725 nm) low resolution spectra were recorded through a long slit (2.3" x 5') aperture with typical exposure times of 15 min, covering 1 hr and 2.5 hr, respectively during the two nights. Calibration spectra using an helium lamp were recorded at 1 hr interval and before and after the observations, from which a typical resolution of 1.3 nm was measured. The standard spectroscopic stars BD+33 2642 and BD+28 4211 were observed during the two nights. The transparency was affected by residual absorption during part of the nights and the resulting variability was corrected by monitoring two additional stars present in the slit.

Figure 1 shows a (2x2)° field-of-view around the position of the X-ray source Cep X-4. The field is rather complex, due to the presence of the low surface brightness nebula, IC1396, ex-

Send offprint requests to: J.M. Bonnet-Bidaud

⋆Based on observations collected at the Observatoire de Haute-Provence, CNRS, France

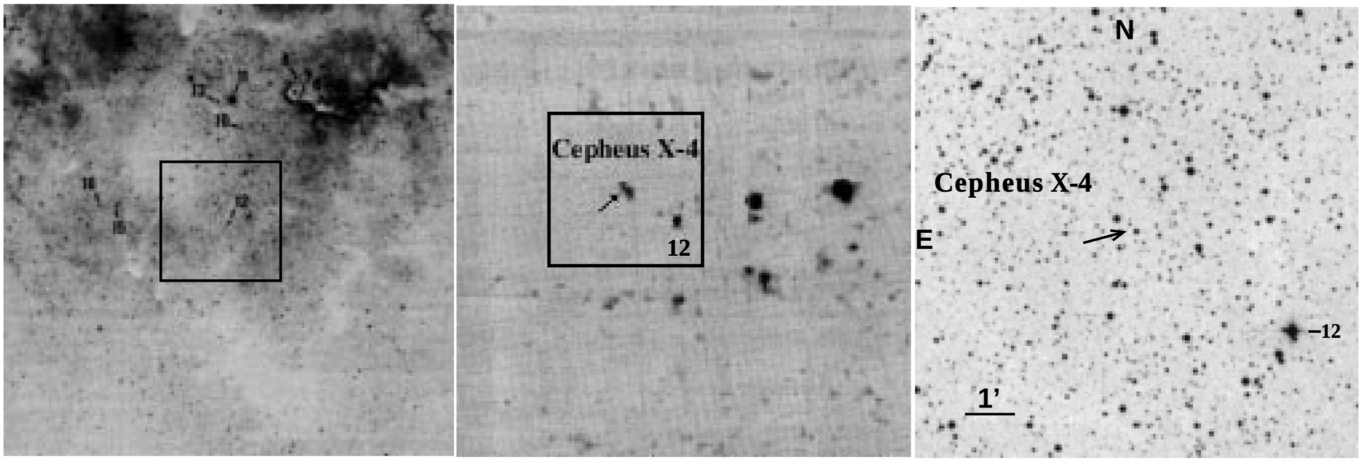

Fig. 1. Optical identification of the transient X-ray pulsar Cepheus X-4 .
a- The (2x2)° optical field around the source showing the intervening nebula IC1396. b- The (30x30 arcmin) ROSAT (0.1-2.5keV) X-ray image during quiescence. c- The (10x10 arcmin) optical image around the X-ray source from the digitized Palomar Sky Survey.

Table 1. Characteristics of the Hα bright Be/X-ray binaries

Source	Emission line EW (nm)			Interstellar line EW (nm)		E_{B-V}	D	Spectral type	References
	$H\alpha^{max}$	$H\alpha$	$H\beta$	*NaD*	*DIB 443 nm*		*kpc*		
GS2138+56	5.3	4.54 (11)	0.33 (2)	0.32 (3)	0.28 (2)	1.1-1.2	3.8(6)	B1V-B2V	
A1118-61	8.9	5.4-6.7	0.45-0.67	0.24 (3)	0.27 (5)	1.2(2)	5 (2)	O9.5III-V	1,2,3
4U1145-61	4.5	1.1-1.5	0.15-0.45	-	-	0.29	3.1(5)	B1V	1,4
A0535+25	3.0	1.0-1.9	0.1-0.2	0.11(2)	0.27 (5)	0.75	2.6(4)	O9.7V	1,5,6

Error bars on last digits are given into parentheses
[1]Reig et al.1997, [2]Motch et al.1988, [3]Mouchet (unpublished), [4]Stevens et al.1997, [5]Janot-Pacheco et al.1987, [6]Wade & Oke 1977

cited by the O6 Trapezium-type system, HD206267 (star 11), itself included in a very young open cluster, Trumpler 37, at a distance modulus of 10.0 (Marschall et al. 1990). The X-ray source is located in the southern part of the nebula, 4.1 arcmin north-east from the bright star HD239725 (star 12). The optical image corresponding to the ROSAT field-of-view is shown in Figure 1c with the identification first proposed by Roche et al. (1997) at the center of the field. Star 12, also detected by ROSAT, is the nearest X-ray source (see fig 1b).
The mean spectrum of the suggested counterpart of Cepheus X-4 is shown in Figure 2. It shows an heavily reddened continuum with a strong H_α line and a weaker H_β line. No other strong emission lines are seen, the other most conspicuous features are atmospheric and interstellar absorption lines. The sky spectrum, also shown in Fig. 2, reveals strong emission lines, including H_α and H_β . It is representative of the rather uniform emission from the excited IC1396 nebula, seen through the entire 5' aperture. The very accurate sky-line subtraction demonstrates that the extracted spectrum is not contaminated by the foreground nebula.
The normalized spectrum is shown in Fig. 3. Except for the H_α and H_β lines in emission, the rest of the Balmer series is seen in absorption down to H_9. The H_γ line, not clearly detected, is the transition from emission to absorption. Such characteristics are usually found in Be stars. Strong absorption features are also visible, including a deep narrow doublet NaD at 589.3 nm (not resolved at the present resolution) and several diffuse interstellar bands (DIB) at 443.0 nm, 577.7 nm, 618.0 nm and 628.3 nm. Other bands are telluric O_2 band at 630.0 and 688.4 nm and atmospheric vapour band at 718.5 nm. We also identify the Fe multiplet complex in emission at 501.7, 517.0 and 531.5 nm, as well as shortward of H_β at 462.8 and 472.8 nm. The only helium line clearly present in this spectrum is HeI at 447.1 nm on the edge of the 443.0 nm DIB and possibly at 471.3 nm. The HeII 468.6 nm, typical of the X-ray heated stars, is not detected nor any significant excess around the CIII-NIII blend (465nm). Several features are not clearly identified, such as a bump around 560 nm and an absorption near 647 nm. Absorption redward of H_β could be an inverse P-Cygni profile sometimes observed in Be stars or a CrI line as suggested for another Be/X-ray binary A1118-61 by Polcaro et al. (1993), but also more likely the 488.5 nm DIB.
Equivalent widths (EW) of the most conspicuous lines are reported in Table 1. Spectral variability has been searched both in the continuum and lines. The H_α and H_β EW were found only slightly variable by 4.4% and 2.5% respectively, while the continuum varies by less than 10 % over the two days of observations. The H_α is broad with a deconvolved FWHM of (530±40) $km.s^{-1}$. Using the empirical relation between the width and EW of the H_α line derived by Dachs et al. (1986), this corresponds to a projected rotational velocity of (460±50) $km.s^{-1}$.

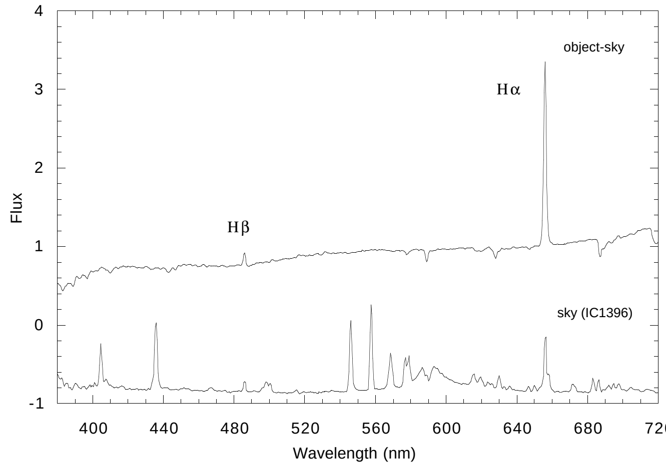

Fig. 2. The mean spectrum of the Cepheus X-4 optical counterpart. Flux after airmass correction, sky subtraction and calibration is shown but without correction for the interstellar reddening. Flux units are 10^{-22} W.m^{-2}.nm^{-1}. Also shown is the mean sky spectrum revealing the presence of the ionized HII region through which the source is seen. The sky spectrum, averaged over 0.1 arcmin^2, have been shifted downward by one unit for clarity.

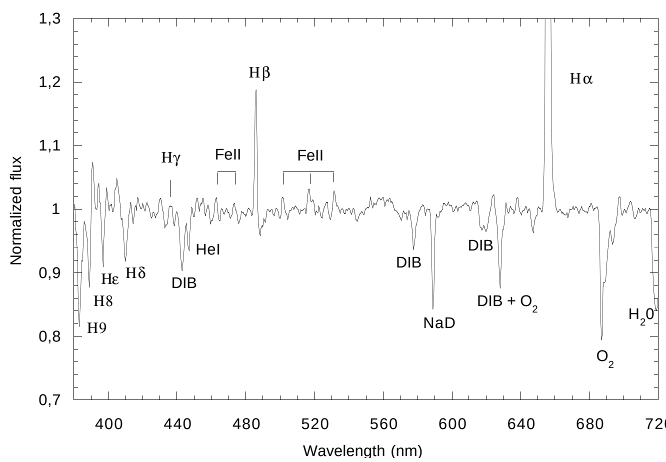

Fig. 3. The source normalized mean spectrum.

3. Discussion

The spectrum of the suggested Cepheus X-4 optical counterpart appears typical of a Be star with a strong H_α line in emission and a Balmer series turning to absorption shortward of H_γ . The probability to find such an active star inside the small (15'x6') error box of an X-ray source is sufficiently low to consider that the object is indeed the optical counterpart of the 66s X-ray pulsar Cepheus X-4 . The significance of the coincidence may be altered as the source is located in the line of sight of the open cluster, Trumpler 37, at the center of an OB association, but a Be star located in the cluster will appear much more luminous (see below). The high excitation HeII (468.6 nm) line is not always present in X-ray stars and its absence here may results from an X-ray low state.

Based on the compilation by Reig et al. (1997), we note that the star is the second brightest in H_α among other identified Be/X-ray binaries (see Table 1). Assuming the approximate linear relation suggested by Reig et al. (1997) between H_α EW and the orbital period, yields an orbit of the order of 130-170 days, of the same order than the $\sim$ 100 days period derived from the P_{spin}-P_{orb} correlation (Koyama et al. 1991).

3.1. Spectral type of the Cepheus X-4 optical counterpart

Significant constraints on the system can be derived from the shape of the continuum. A sample of representative spectra from O8 to B7 stars among classes III and V was selected from the library of Jacoby et al. (1984) and the continuum in regions free of lines was fitted, using standard χ^2 method, to the observed source spectrum after correcting for interstellar absorption. Dereddening was applied according to the mean galactic law of Seaton (1979) with values of E_{B-V} ranging from 0 to 2.0.

Figure 4 shows the result of the fit. The best agreement is obtained for E_{B-V}=1.3±0.1, where the range corresponds to 1σ error bars for a 2dim-χ^2 fit. The fit only loosely constrains the spectral type between 09V and B4V. However, additional clues on the nature of the star are also given by the line spectrum. The absence of the HeII Pickering series is consistent with a spectral type at or later than B0 (Walborn and Fitzpatrick 1990) while the presence of the HeI lines in absorption constrains to types earlier than B5-B7 (Collins & Sonneborn 1977). The HeI lines may however be affected by the veiling effect, a filling of the underlying absorption spectrum by the emission from the envelope. On the other hand, the FeII lines are clearly seen, which, according to Jaschek et al. (1980) is expected from spectral types peaking at B2. This is also in accordance with the absence of significant SiII (412.8 nm) and MgII (448.1 nm) lines whose contribution increases towards types later than B2 (Walborn & Fitzpatrick 1990), though the moderate resolution somewhat limits this conclusion. The most probable spectral type is therefore a B1-B2V star.

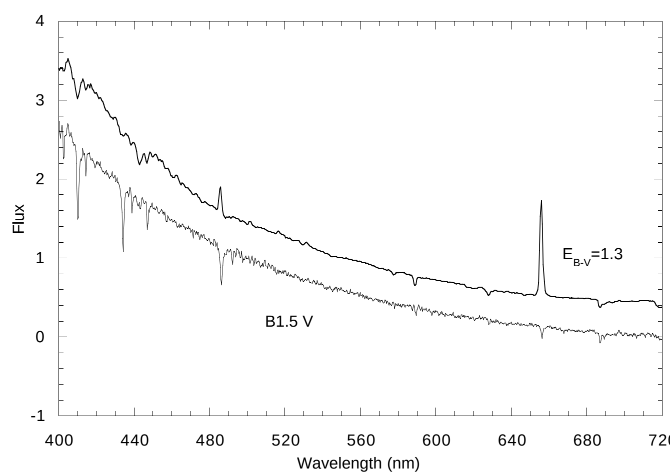

Fig. 4. Best fit of the observed optical continuum. The source has been corrected for absorption with E_{B-V}=1.3 and a B1.5V representative spectrum is shown shifted by 0.4 unit for clarity.

3.2. Absorption towards Cepheus X-4

A significant amount of interstellar absorption is visible in the spectrum with a strong NaD line with EW=0.32±0.03 nm and pronounced diffuse interstellar bands, including the DIB (443 nm) with EW = 0.28±0.02 nm (see Table 1). Based on observations of stars with E_{B-V} ranging from 0 to 1.5, a nearly linear relation between the EW of the DIB(443 nm) and the colour excess E_{B-V} has been derived by various authors. From the observed DIB EW, values of E_{B-V}=1.1-1.3 and E_{B-V}=1.0-1.2 are derived, using relations by Herbig (1975) and Tüg & Schmidt-Kaler (1981) respectively. These values are consistent with the one derived from the continuum fit.

A discrepant result is however obtained if one uses the NaD line as a tracer of interstellar absorption. Using the parabolic relation NaD1/E_{B-V}, recently derived by Munari & Zwitter (1997) from observations of nearby stars, and assuming equal contribution from each component of the doublet, a value of $E_{B-V} \sim 1.3$ would correspond to a NaD EW of ∼ 0.15 nm, approximatively half the observed value. The observed NaD in Cepheus X-4 is indeed the highest among the sources in Table 1, irrespective of the distance. This could result from peculiar abundances in the interstellar medium but also more likely from possible circumstellar contribution. Circumstellar sodium has been reported in the Be shell star ζ Tau by Delplace (1970) with EW up to 0.26 nm. The observed excess of EW∼0.17 nm, could possibly have the same origin. We note that such absorption is usually detected mostly among Be "shell" stars. The high rotational velocity derived from the H_α line width (460 km.s^{-1}) is close to the break-up velocity (470-520) km.s^{-1} of B1-B2V stars (Collins & Sonneborn 1977), so that an inclination of the equatorial plane greater than (65-80)° is indicated, which could explain the similarity of Cepheus X-4 with the Be-shell class.

3.3. Location in the Galaxy

Reddening towards the star HD239725 (star 12), in the foreground open cluster Trumpler 37, at a projected small distance of the source, has been measured to E_{B-V}=0.46 (Clayton & Fitzpatrick 1987), so that the Cepheus X-4 counterpart is clearly located behind the cluster. Assuming a standard gas-to-dust ratio (Ryter et al. 1975), the reddening implies a N_H column density in the direction of the source of N_H = (8.8±0.8) 10^{21} at.cm^{-2}. This value is in good agreement with the X-ray column density of N_H = (7.9±1.9) 10^{21} at.cm^{-2} derived by Schulz et al. (1995) from X-ray spectra. With a mean interstellar density $n_e < 1$ at.cm^{-3}, this corresponds to a distance greater than (2.9±0.2) kpc. At a galactic position of (l^{II}=99.01°, b^{II}=+3.31°), the source is located in the plane of the Galaxy in the direction of the outer Perseus arm. The total column density of neutral hydrogen at this position is $N_{HI} \sim$ 9.4 10^{21} at.cm^{-2} (Dickey & Lockman 1990) so that the source is close to the most outer part of the Galaxy. In this direction, the Leiden-Greenbank HI survey (Burton 1985) clearly reveals distinct galactic structures at v∼-10 km.s^{-1} and v∼-80 km.s^{-1}. Based on a detailed HI study of this region, Simonson & van Someren Greve (1976) concluded to the superposition of three separate galactic contributions, a local star population at ∼ 400 pc, the Cep OB2 association including the IC1396 nebula at ∼ 830 pc and a group of luminous stars at 3-5 kpc which corresponds to the Perseus arm. In view of this galactic structure and of the distance derived from reddening, it is most likely that the Cepheus X-4 counterpart belongs to this last group.

The observed m_V=14.2 magnitude with a reddening of E_{B-V}∼1.3 and an absolute magnitude of Mv=-(2.5-3.8), corresponding to B1V-B2V stars (Balona & Crampton 1974) as indicated by our spectral results, corresponds to a distance D=(3.8±0.6) kpc in accordance with such location.

With the lack of distance determination and the spatial coincidence with the Cep OB2 association, Schulz et al. (1995) have suspected that the X-ray source may be located at D< 1kpc, leading to the weakest observed quiescence luminosity among Be/X-ray binaries. Our distance determination implies instead a luminosity in quiescence, Lx(0.1-100keV)=(3.3-6.2) 10^{33} erg.s^{-1} and in outburst Lx=(0.6-1.2) 10^{37} erg.s^{-1}, in the normal range of what is observed among typical Be/X-ray binaries (Apparao 1994).

In conclusion, optical spectra of the Cepheus X-4 transient X-ray pulsar appear fully consistent with a Be/X-ray system located at a distance of D∼4kpc, in the outer Perseus arm of the Galaxy. The optical spectrum indicates a B1-B2V companion showing one of the strongest H_α emissions among Be/X-ray binaries and a significative excess of absorption in the sodium line with respect to what expected from a purely interstellar origin. This and the determination of the radial velocity curve clearly deserve further optical studies.

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References

Apparao K.M.V., 1994, Space Sc. Rev. 69, 255
Argyle R.W., 1997, IAU Circ. 6711
Balona L., Crampton D., 1974, MNRAS 166, 203
Bonnet-Bidaud J.M., Mouchet M., 1997, IAU Circ. 6724
Burton W.B., 1985, A&AS 62, 365
Clayton G.C., Fitzpatrick E.L., 1987, AJ 93, 157
Collins II G.W., Sonneborn G.H., 1977, APJS 34, 41
Dachs J., Hanuschik R., Kaiser D., Rohe D., 1986, A&A 159, 276
Delplace A.M., 1970, A&A 7, 459
Dickey J. M., Lockman F. J., 1990, ARA&A, 28, 215.
Hensberge G., Hammerschlag R.H., 1975, A&A 39, 157
Herbig G.H., 1975, ApJ 196, 129
Jacoby G.H., Hunter D.A., Christian C.A., 1984, APJS 56, 257
Janot-Pacheco E., Motch C., Mouchet M., 187, A&A 177, 91
Jaschek M., Hubert-Delplace A.-M., Hubert H., Jaschek C., 1980, A&AS 42, 103
Koyama K., Kawada M., Tawara Y., et al., 1991, ApJ 366, L19
Lemaitre G., Kohler D., Lacroix D. et al., 1990, A&A 228, 546
Liller W., 1974, IAU Comm. 42, Circ Letter 2
Marschall L., Comins N. Karshner G., 1990, AJ 99, 1536
Mihara T., Makishima K., Kamijo S., et al., 1991, ApJ 379, L61
Motch C., Janot-Pacheco E., Pakull M., Mouchet M., 1988, A&A 201, 63
Munari U., Zwitter T., 1997, A&A 318, 269
Polcaro V.F., Villada M., Giovannelli F., 1993, A&A 273, L49
Reig P., Fabregat J., Coe M.J., 1997, A&A 322, 193
Roche P., Green L., Hoenig M., 1997, IAU Circ. 6698
Ryter C., Cesarsky C., Audouze J., 1975, ApJ 198, 103
Schulz N.S., Kahabka P., Zinnecker H., 1995, A&A 295, 413
Seaton M.J., 1979, MNRAS 187, 73P
Simonson III S.C., van Someren Greve, H.W., 1976, A&A 49, 343
Stevens J., Coe M., Reig P., Steele I., 1996, MNRAS 288, 988
Tüg H., Schmidt-Kaler Th., 1981, A&A 94, 16
Ulmer M.P., Baity W., Wheaton W. et al., 1973, ApJ 184, L117
Wade R., Oke J., 1977, ApJ 215, 568
Walborn N.R., Fitzpatrick E.L., 1990, PASP 102, 379

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