High angular resolution observations of late-type stars

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Based on observations made with the *Télescope Bernard Lyot* at Pic du Midi Observatory, France.

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ABSTRACT

This paper presents speckle observations of Mira (o Cet) and late-type stars with the PISCO speckle camera of Pic du Midi during the period 1995-1998. A survey for binarity among a sample of late-type stars was performed, which led to 7 positive detections out of 36 objects. Photometric and color variations of the companion of Mira were searched for, but no significant brightness variations could be found over a time scale of ∼5–10 minutes. The position and photometry measurements, the restored images with high angular resolution of the binary system Mira A-B (ADS 1778) are in full agreement with HST data obtained at the same epoch. A new orbit has been derived for Mira A-B.

Subject headings: Stars : late-type - Stars : individual : o Cet - Binaries: close - Methods: data analysis – Techniques: interferometric

1. Introduction

How an evolved star loses a significant fraction of its material on its way to planetary nebula, has been for long, and still remains, a fundamental problem in stellar evolution. The physical processes underlying the mass loss, such as the connection between the large scale winds and phenomena occurring at or below the photospheres of evolved stars (pulsation, convection) are poorly understood (Lafon and Berruyer, 1991). Besides, aspherical morphologies are observed for the envelope of the majority of planetary nebulae, as well as, earlier in the evolution, during the post-AGB (Asymptotic Giant Branch) stage. Morris (1981) suggests that the material lost by a red-giant may be deflected by the presence of a companion. From an observationnal point of view, this binary model has been strengthened by recent observations of post-AGB sources : adaptive optics images of the Frosty Leo nebula (Roddier et al. 1995) and spectrometric measurements of the Red Rectangle nebula (Van Winckel et al. 1995). The importance of the presence of a companion for the evolution of late-type stars motivated us to start a program of speckle observations of Mira and other late-type stars.

The close (0.4 arcsec) companion of Mira was discovered by Joy (1926) during spectroscopic observations at Mira's light minimum of 1923. Its long-period orbit, with a first estimate of $P \sim 400$ yr as determined by Baize (1980), shows perturbations with a time-scale of ~ 34 yr which suggests the presence of a third body, not yet detected (Baize, 1980). Position measurements are difficult to perform due to the closeness of the two stars and the large brightness contrast between Mira A and B during most of the time; they are possible only at Mira minimum. Recent measurements of the system were successfully performed using speckle interferometry (Karovska et al. 1993) and the HST (Karovska et al. 1997).

Mira B is also a variable star with a maximum around $m_V = 10$ and a 14 yr period (Joy 1954, Yamashita and Maehara, 1977). It is located at $M_v \sim 5.5 - 7.5$ in a region in the H-R diagram between the white dwarf sequence and the main sequence where subluminous hot objects like old novae and cataclysmic variables are found. The relationship to such objects was further strengthened by the photometric variations reported by Warner (1972), who found substantial brightness variations on a time scale of hours, variations of $\sim 10\%$ on a time scale of 15 minutes and rare "flares". This was in agreement with old visual observations of night to night variations by 1 mag (Joy, 1954). More recently, UV observations with IUE (Reimers and Cassatella, 1985) also showed brightness variations up to 30%. An explanation for this phenomenon, first proposed by Deutsch (1958) is that Mira B is a white dwarf surrounded by a much brighter accretion disk which is fed by materiel from the extended circumstellar shell of Mira A. Hence the Mira system would provide a chance to study the "simple" case of an accretion disk around a white dwarf formed in the stellar wind at a large distance from the mass-losing star.

As shown by the example of Mira, the study of binary Mira-type stars is particularily interesting to understand the symbiosis of this type of binary and the link with the mass-loss mechanism of the red giant. In the catalogue of variable visual binary stars made by Proust et al. (1981), only 30 Mira-type stars are mentioned. This surprising deficiency prompted us to contribute through a survey program to search for binarity among Mira stars and other late-type stars, and add new position measurements for future orbit determination.

In Sect. 2 and 3 we describe the observational procedure of the speckle measurements, its limitations and the strategy that we adopted. In Sect. 4, we present the high angular resolution observations of Mira whose aim was (i) to provide new position measurements (ii) to detect possible brightness/color variations that would result from interactions between Mira B and the circumstellar shell of Mira A. In Sect. 5 we present the results of our search for binarity in a sample of 35 late-type stars and in Sect. 6 we compare our measurements with the ephemerides derived from the available orbits for Mira and X Oph.

2. Observations

Photometric observations of Mira were performed on Dec 11th 1995. Other observations for this programme were carried out in Dec 1995, Jan 1997, June 1997, June 1998, and August

1998 for a total of 11 nights. The instrumentation was the PISCO[1] speckle camera (Prieur et al. 1998), developed by *Observatoire Midi-Pyrénées* and operated at the Cassegrain Focus of the 2-meter *Télescope Bernard Lyot* of Pic du Midi Observatory. It is a remotely controlled versatile instrument that can be configured in various observing modes during the observations (i.e., direct imaging, spectroscopy and pupil imaging) which provides a powerful tool for investigating the field of close binary stars as already shown in previous publications (Aristidi et al. 1997, 1999, Scardia et al. 2000, Prieur et al. 2000).

PISCO was used in its direct imaging mode with the ICCD (intensified CCD with a multichannel plate) of Nice University (see Aristidi et al. 1997, for a presentation), whose analog output was recorded on SVHS video tapes at a rate of 50 frames/sec.

Stars were observed during 5 to 20 minutes depending on their magnitude. For each target star a close reference star was observed in the same experimental conditions (sometimes a neutral density filter was added to adjust fluxes).

3. Observational limitations

The large brightness ratio between the main star and its companion is a central problem in this study. Late-type stars are giant and very luminous, whereas possible companions are main-sequence stars or white dwarfs with very low luminosity. In the case of Mira, the companion itself varies between 10th and 12th mag (Joy, 1954). Since the maximum dynamic range attainable by speckle interferometry is around 5 mag, Mira B is undetectable when Mira A is close to its maximum. As a consequence, speckle observations had to be made as close as possible to the minimum of luminosity of the primary. Note also that the limiting magnitude for our experiment is $V \sim 10$ for medium seeing conditions (Aristidi et al. 1997), which constitutes a limit for the detection of the companions.

To reduce the contrast between the possible companion and the main star, observations were done with the shortest possible wavelength, e.g. through the blue filter (B), but very often the seeing conditions in the blue and the bad sensitivity of the detector made these observations difficult, if not impossible. Most of the time the green filter (V) was a better compromise. We made some attempts with the red filter (R) for some very faint stars, sometimes with success. Filters characteristics are B: $\lambda_c = 447$ nm, $\Delta\lambda = 57$ nm, V: $\lambda_c = 530$ nm, $\Delta\lambda = 57$ nm, and R: $\lambda_c = 644$ nm, $\Delta\lambda = 70$ nm (where λ_c is the central wavelength and $\Delta\lambda$ is the width at half maximum).

[1]PISCO stands for "Pupil Interferometry Speckle camera and COronagraph".

4. Mira A-B binary system: image restoration and relative photometry

Except in Sect. 4.2.2 which is about data from 1998, this section refers to the photometric observations of December 11th 1995.

4.1. Data processing - Photon noise bias correction

The SVHS tapes were digitized with a Next workstation with a format of 128x128 pixels. The observations of Mira were split into 9 sequences of 5 minutes each. Then the elementary frames were processed to derive a mean bispectrum and a mean power spectrum for each data set. These two steps were rather lengthy due to the large number of frames. We finally restored images for each sequence and performed photometric measurements (Sect. 4.2).

As the target was faint, the intensity was low and the ICCD was working in a regime close to the photon-counting mode with non negligible quantum noise effects. For a full image restoration and/or photometry measurements, the mean power spectra and bispectra thus needed to be corrected for photon noise bias (Dainty & Greenway, 1979, Nakajima, 1988), which is always difficult with analog detectors which do not provide the coordinates of each detected photon as other genuine "photon-counting detectors" such as the PAPA, CP40 and CAR (Prieur et al. 1998) would do. The main problem in that case is the accurate determination of both N_{ph}, the mean number of detected photons per frame, and the response of the detector to one photon (which may vary with time). To check the reliability of our results, we applied two different methods based on a correction of either (i) each elementary frame, or (ii) on the averaged bispectra and power spectra.

Method 1: a posteriori "photon detection" The search for individual photo-events was performed on each elementary frame by scanning it thoroughly, looking for local maxima and then setting all the neighbouring pixels to zero. This filter reduced greatly the artefacts associated with the photon response of the ICCD and the low spatial frequency background noise on the elementary frames. The mean power spectrum and bispectrum was then computed with these filtered frames.

Method 2: correction for the photon response on the averaged quantities Here the starting point was the mean bispectrum and power spectrum derived from the original elementary frames on which only a threshold had been applied to remove the video noise. Then a correction for the photon response was applied on the mean power spectrum, by dividing it by the mean power spectrum of the photon response, obtained with a "flat field" with low illumination.

In both cases, the correction of photon noise bias was then done on the derived mean bispectrum and power spectrum with N_{ph} determined by measuring the level of the power spectrum at high spatial frequencies.

4.2. Image restoration

4.2.1. Image in B (December 11th 1995)

Because of the poor signal to noise ratio of the data, the bispectral method (Prieur et al. 1991) failed for all sequences and led to quasi-symmetric images similar to the auto-correlation function with a central peak and two secondary components, the brightest being in the West, which is in agreement with the HST image taken on the same day (Karovska et al. 1997).

Hence, for the image restoration of the 5-10 min sequences that were needed for the photometric measurements, we used instead an iterative deconvolution method, with a constraint on the measured power spectrum in the Fourier domain and a support constraint in the image domain, based on our knowledge of the binary structure of the object. Provided that the support in the image plane be properly positioned and well matched to the angular resolution, this procedure was rather robust and not sensitive to the starting point with a convergence in ∼5-8 iterations.

The restored image of the Mira system, obtained with all the available data from December 11th 1995, is shown in Fig. 1a.

4.2.2. Image in V (August 29th 1998)

In August 1998, the quality of the observations in V was good enough to allow full image restoration with the bispectral method developed by our team, without any need for a priori information (cf. Prieur et al., 1991). The corresponding image is shown in Fig. 1b and led to a measurement of $\Delta m_V = 1.0 \pm 0.15$.

4.3. Relative photometry of Mira B

The photometric measurements derived from the restored images are presented in Fig 2. They do not show any significant variation of relative brightness over a time scale of 5 or 10 minutes, within the error bars which are larger than ∼0.15 mag. The limited quality of the data and the level of the photon noise could not lead to a higher accuracy. In addition to the two methods described in Sec. 3, we have also attempted to derive the relative photometry of Mira B by means of the probability imaging technique (Carbillet et al. 1998). Unfortunatly, the technique while very effective at good SNR values, resulted in too much sensitivity to the noise and led to much less accurate results than those presented in Fig. 3.

The mean value of Δm_B is 1.2±0.15 mag, which is compatible with the values found by Karovska et al. (1997): Δm=1.36 at 410 nm and Δm=0.16 at 471 nm.

5. Search for companions around late-type stars

5.1. Description of our sample

The list of late stars observed by Hipparcos and suspected as double was taken as a starting point for defining our sample. Some of these stars were already known as double such as R And or X Oph, but most of them were only new suspected double stars whose binarity needed confirmation. The objects of our list are evolved stars surrounded by a dust envelope: late AGB, post-AGB, Miras and carbon stars. Spectral class of these stars ranges from late K to M with a color index $V - R$ ranging from 1.2 to 3. All these stars are variable with sometimes a large amplitude: $\Delta m_V \sim 7$ mag for Mira.

5.2. Data analysis

Single video frames were processed by averaging power spectra over the whole sequence. If a companion was detected, the angular separation was computed using the mean autocorrelation. Absolute quadrant determination was made using the mean cross-correlation between images and their square. Eventually when the SNR was good enough, relative photometry was derived from probability imaging. The whole procedure is described in more detail in Aristidi et al. (1997).

5.3. Results of the binary survey

The characteristics of our sample and the results of our survey are presented in Table 1. The V magnitude from the Simbad astronomical database, respectively at the brightness maximum and minimum are in cols. 4 and 5. The V magnitude at the epoch of observation, taken from AAVSO database, is in col. 7. When a companion could be detected, the angular separation ρ is given in col. 9, its position angle θ (relative to the North and increasing to the East) in col. 10, and its relative photometry in col. 11.

Table 1. List of our sample and results of the survey.

HIP (1)	Name (2)	Type (3)	Vmax (4)	Vmin (5)	Epoch (6)	V (7)	Filt. (8)	ρ (arsec) (9)	θ (deg.) (10)	Δmag (11)
1834	T Cas	Mira	7.3	12.4	1995.942	11.5	V	—	—	—
1901	R And	Mira	6.0	14.9	1995.942	10.5	V	—	—	—
7139	IM Cas				1995.942		V	—	—	—
10829	T Per	SR	8.2	9.1	1995.951	8.8	V	—	—	—
10826	Mira	Mira	2.0	10.1	1995.942	9	V	—	—	—
”	”	”	”	”	1995.945	9	B	0.62 ± 0.02	108± 2	1.2±0.15
”	”	”	”	”	1998.657	9	B	0.57 ± 0.01	106± 3	—
”	”	”	”	”	1998.657	9	V	0.59 ± 0.01	110± 1	—
”	”	”	”	”	1998.660	9.5	B	0.56 ± 0.02	110± 2	—
”	”	”	”	”	1998.660	9.5	V	0.583 ± 0.002	110.0±0.5	1.0±0.15
17257	U Cam	C*	11.0	12.8	1995.942	8.5	V	—	—	—
21046	RV Cam	SR	8.2	9.0	1995.939	$\simeq$ 8	R	0.070± 0.004	222 ± 1	2.3±0.3
”	”	”	”	”	1997.068	$\simeq$ 8	V	—	—	—
21059	RY Cam	SR	8.9	11.0	1995.939	8.4	R	0.062 ± 0.008	325 ± 1	1.9±0.2
”	”	”	”	”	1997.068	8.2	V	0.1 ±0.02	350 ± 8	—
22552	ST Cam	C*	9.2	12.0	1995.942	7.5	R	—	—	—
27135	TU Tau	C*	11.1	12.5	1995.942	8.5	V	—	—	—
29896	GK Ori	C*	9.5	11	1997.068		V	—	—	—
31379	RV Aur	SR	11.8	13.1	1997.068		V	—	—	—
33450	UW Aur	SR	9.7	11.6	1997.068		V	—	—	—
33824	R Lyn	Mira	7.2	14	1995.942	8.4	V	—	—	—
41058	T Lyn	Mira	10.1	14.8	1995.942	11.5	V	—	—	—
49224		—	7.5	7.5	1995.942		V	0.634 ± 0.006	93.5 ± 0.2	2.4 ±0.4
61532	T Uma	Mira	6.6	13.4	1995.939	11	R	—	—	—
”	”	”	”	”	1998.438	7.8	V	—	—	—
”	”	”	”	”	1998.438	7.8	R	—	—	—
78307	AH Ser	Mira	11	>12.5	1997.482	12.5	R	—	—	—
79233	RU Her	Mira	11.6	>13.8	1997.496	13	R	—	—	—
80259	RY CrB	SR	9.2	10.4	1997.482		V	—	—	—
80550	V Oph	Mira	7.3	11.6	1997.482	10	V	—	—	—
81506	AS Her	Mira	9.9	15.3	1997.496	10	V	—	—	—
84346	V438Oph	SR	9.3	11.6	1997.482		V	—	—	—
87820	T Dra	Mira	7.2	13.5	1997.496	12	V	—	—	—
”	”	”	”	”	1998.438	12.4	V	—	—	—
”	”	”	”	”	1998.438	12.4	R	—	—	—
88923	T Her	Mira	6.8	13.6	1997.496	12	R	—	—	—

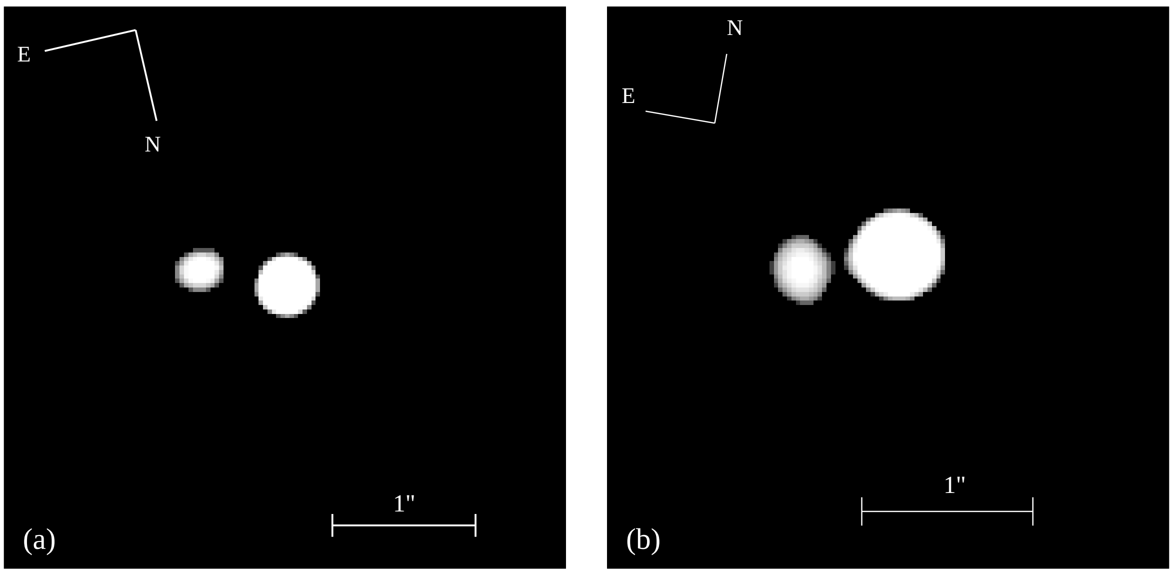

Fig. 1.— Restored images of Mira and its companion. (a) mean of all B data from December 11th 1995, corrected by method 2 and restored using the iterative process described in Sect. 4.2. (b) V data from August 29th 1998, corrected by method 2, and restored with bispectral method. For both images, the companion is on the left.

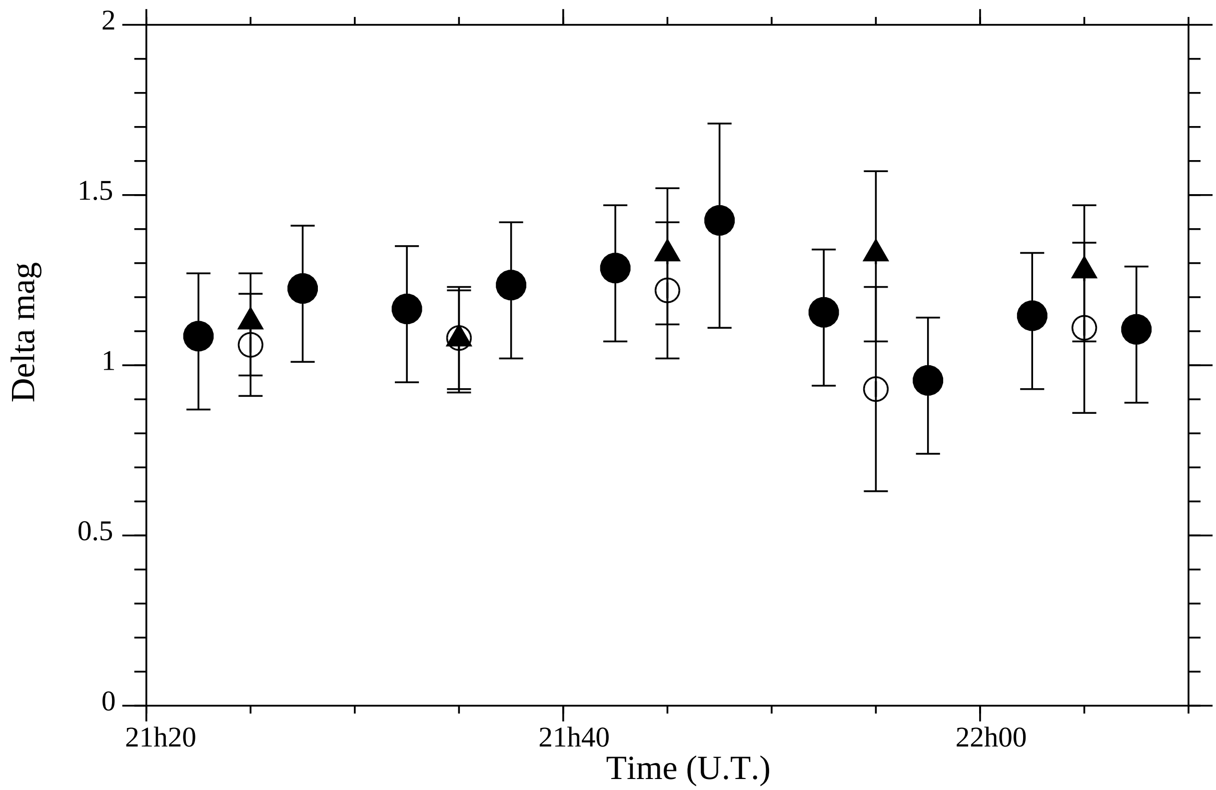

Fig. 2.— Relative photometric measurements of Mira and its companion measured on Dec. 11th 1995 in B, with various methods: method 1 with sequences of 5 min (filled circles) and 10 min (open circles), method 2 with 10 min sequences (filled triangles).

Out of the 36 objects of the list, we found 7 binaries. As we observed with different filters or at different epochs, this corresponds to 13 positive detections out of 56 independent observations:

- The stars Mira and X Oph were previously known as binary stars, with a computed orbit. Our measurements are compared with the ephemerides derived from these orbits in Sect. 6.

- RV Cam, RY Cam, SV Peg and W Cep were new binaries discovered by Hipparcos. Our observations with respectively 1, 2, 2 and 1 positive detections confirm their binary nature. Visibility curves obtained for RV Cam and RY Cam are shown in Fig. 3. Autocorrelation functions computed for SV Peg and W Cep are shown in Fig. 4.

  In Table 5.3 we compare Hipparcos measurements (epoch 1991.25), with our measurements (epoch in the range 1995-1998). We note that the Hipparcos values are rather different from ours, which may come from two different origins: (i) the orbit has a short period and the orbital motion is significant between these epochs (which seems verified for SV Peg, whose position angle covered nearly 90 degrees in 7 years), (ii) Hipparcos measurements are sometimes doubtful when close to its limits, i.e., for separations around 0.1-0.2 arcsec and large magnitude difference, which is the case here (see col. 11 of Table 1). Let us remind that we expected such differences, since one of the goals of this program was to check the validity of Hipparcos binary discoveries for late-type stars.

- HIP 49224 is a non variable G-type star; its presence here results from a mistake in the target list. Hipparcos measurements, $\rho = 0.728$ arcsec, $\theta = 93^\circ$, are close to our measurements.

No companion was detected for the other observed stars. As usual for negative detections, we cannot really conclude for these stars. The absence of detection may have many observational causes: (i) the companion was too faint ($\Delta m > 5$), (ii) the angular separation was too small ($\rho < 50$ mas), or (iii) the experimental conditions were too bad. For instance, for SV Peg, we detected the companion twice out of the 4 independent observations of this object, each time with the R filter. As mentioned in Sect. 3, the atmospheric turbulence is less severe in the red part of the spectrum (since the coherence radius r_0 varies as $\lambda^{6/5}$), but the relative brightness of the companion is smaller: the mira dominates in R. It is a matter of trade-off according to the atmospheric conditions. For Mira, in 1995, we detected the companion in B, but the contrast was too high in V.

Table 1—Continued

HIP (1)	Name (2)	Type (3)	Vmax (4)	Vmin (5)	Epoch (6)	V (7)	Filt. (8)	ρ (arsec) (9)	θ (deg.) (10)	Δmag (11)
91389	X Oph	Mira	5.9	9.2	1997.482	8.6	*V*	0.480 ± 0.005	312.1 ± 0.2	0.1 ±0.5
91703	FI Lyr	C*	9.5	10.5	1997.482		*V*	—	—	—
93158	UV Aql	SR	11.1	12.4	1997.496	9.4	*V*	—	—	—
98909	X Sge	SR	8.7	9.7	1997.496	8.5	*V*	—	—	—
99503	S Aql	SR	8.9	12.4	1997.496	9.2	*R*	—	—	—
100219	U Cyg	Mira	6.7	11.4	1998.438	8	*V*	—	—	—
”	”	”	”	”	1998.438	8	*R*	—	—	—
101023	RW Cyg	SR	10.5	12.4	1998.438	8.6	*V*	—	—	—
”	”	”	”	”	1998.438	8.6	*R*	—	—	—
102082	V Cyg	Mira	7.7	13.9	1998.438	12.8	*R*	—	—	—
107036	RU Cyg	SR	9.2	11.6	1997.496	8.3	*V*	—	—	—
”	”	”	”	”	1998.438	8.5	*B*	—	—	—
”	”	”	”	”	1998.438	8.5	*V*	—	—	—
107242	RV Cyg	C*	10.8	12.4	1998.438	8.2	*V*	—	—	—
109070	SV Peg	SR	9.4	11	1995.945	8.2	*R*	0.5 ± 0.1	287 ± 2	1.7 ± 0.2
”	”	”	”	”	1995.945	8.2	*B*	—	—	—
”	”	”	”	”	1998.438	8.1	*V*	—	—	—
”	”	”	”	”	1998.438	8	*R*	0.440 ± 0.004	334.2 ± 0.2	0.37 ± 0.07
111592	W Cep	SR	8.9	10	1995.951	7.9	*V*	—	—	—
”	”	”	”	”	1997.496	8	*V*	0.262 ± 0.001	88.3 ± 0.5	1.3 ± 0.3

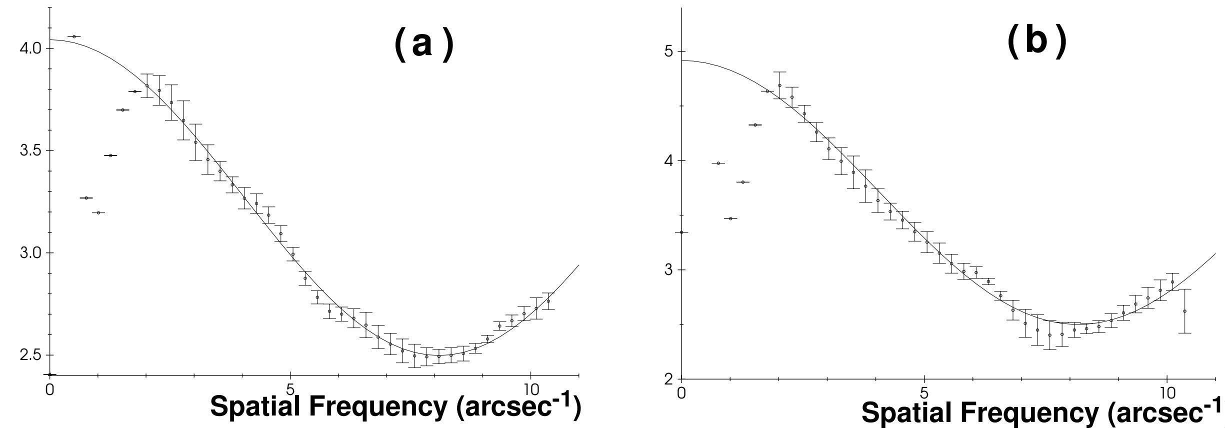

Fig. 3.— Visibility functions for RV Cam (a) and RY Cam (b) (Dec. 1995). Telescope cutoff frequency is at $f_c = 15$ arcsec^{-1}. These curves are slices of the two-dimensional ratio of the power spectrum of each system divided by the power spectrum of a reference star. In each case, 7000 elementary frames have been selected among the best ones according to the classification procedure described in Aristidi *et al.* (1997), for both the double and reference stars.

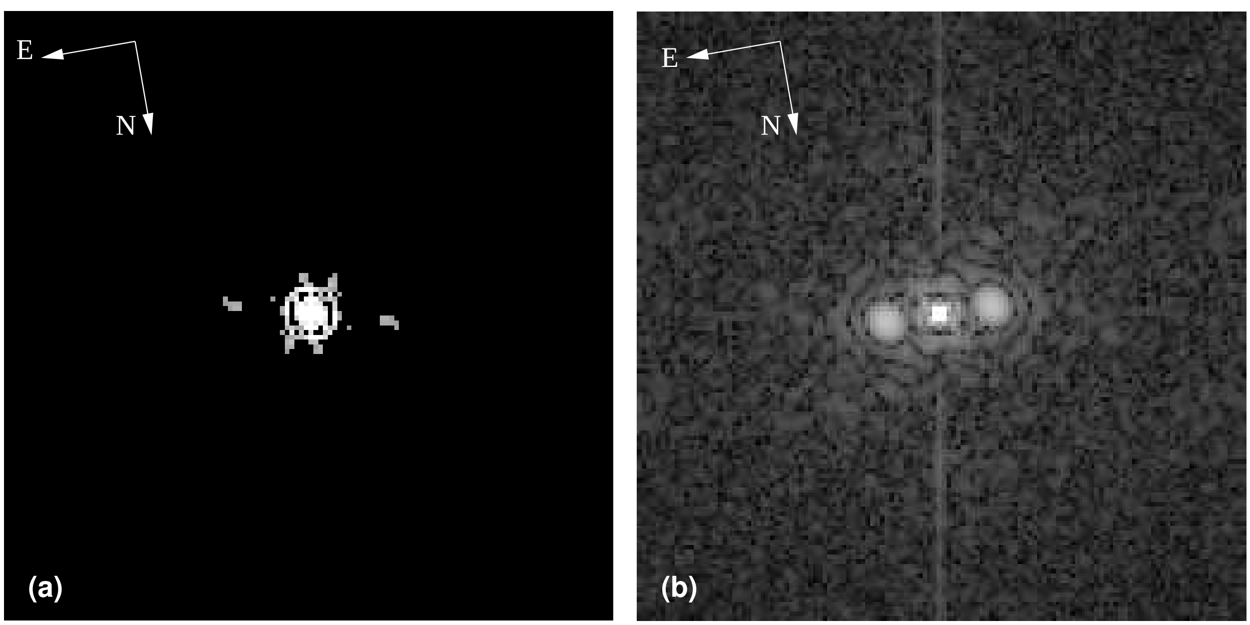

Fig. 4.— Two-dimensional autocorrelation functions for (a) SV Peg (Dec. 1995) and (b) W Cep (June 1997). These functions have been computed respectively for 4000 and 14000 elementary frames (both for the double and reference stars).

Object	Epoch	ρ (arcsec)	θ (degrees)	Δmag
RV Cam	1991.25	0.22	77.	0.1
”	1995.94	0.07	222. (42)	2.3
RY Cam	1991.25	0.16	79.	0.7
”	1995.94	0.06	325. (45)	1.9
”	1997.07	0.1	350. (70)	—
SV Peg	1991.25	0.32	75.	0.5
”	1995.95	0.5	287. (107)	1.7
”	1998.44	0.44	334. (154)	0.4
W Cep	1991.25	0.12	189.	0.1
”	1997.50	0.26	88. (268)	1.3

Table 2: Comparison of our measurements (epoch 1995-1998) with those made by Hipparcos (epoch 1991.25). In col. 4, in brackets: other possible value due to the 180-ambiguity of the speckle measurements.

6. Orbits of Mira and X Oph

Orbital solution for Mira A-B (ADS 1778 - Joy 1) and X Oph (ADS 11524 - HU 198) was given by Baize (1980) and yielded, for our measurements:

Star	Epoch	ρ_C $''$	θ_C $\circ$	ρ_{O-C} $''$	θ_{O-C} $\circ$
Mira (B)	1995.942	0.134	65.5	0.49	43
” (B)	1998.657	0.107	29.7	0.463	76.3
” (V)	1998.657	0.107	29.7	0.483	80.3
” (B)	1998.660	0.107	29.7	0.453	80.3
” (V)	1998.660	0.107	29.7	0.476	80.3
X Oph (B)	1997.438	0.431	133.5	0.049	179.1

where the subscript C stands for *computed* and O for *observed*.

As pointed out by our anonymous referee, many papers report ephemerides of Mira from an orbit that would have been derived by Couteau in the early 1980's, as mentioned in the paper by Reimers and Cassatella (1985). We have not found any published orbit of this binary star from Couteau in the litterature. In particular, we have checked among all the orbits published in the Circulars of the late 1970's and in the 1980's. The confusion comes from an error in the paper by Reimers and Cassatella (1985). These authors attribute to

Paul Couteau an orbit which was actually computed by Paul Baize. Reimers and Cassatella's orbit elements in page 185 are the same as Baize (1980)'s elements. It is likely that Couteau has communicated Baize's orbit elements to Reimers and Cassatella, since Couteau was the editor of the IAU Circulars during that epoch. Indeed, Baize's orbit is also in Worley-Heintz's orbit catalogue (1983) and in the last Navy Catalogue, published this year. All other authors have simply reproduced Reimers and Cassatella's error without checking the validity of its origin.

Our measurements of X Oph are consistent with Baize's orbit if we add 180° to the position angle (quadrant ambiguities occur frequently when the magnitude difference is small). We checked the consistency of the 20 observations of X Oph performed after 1979, with the orbit derived by Baize (1980), which is the only one available (Fig. 5). The corresponding residuals O-C are still very good, with a mean value close to zero and smaller than its standard deviation: $\langle\Delta\rho\rangle$=0.025±0.038 arcseconds, $\langle\Delta\theta\rangle$=-0.37±2.6 degrees. Hence Baize's orbit is still valid for this system and does not need revision until a substantial amount of new observations are performed.

On the contrary, our measurements of Mira are quite different from Baize's ephemerides, but close to the measurements of Karovska et al. (1997) made almost the same day: $\rho =$ 0.578 arcsec, $\theta = 108.3°$, epoch=1995.9424. As already noted by Karovska et al. (1993), this orbit needed revision.

Taking into account all the available observations (see Fig. 6 and Table 4), we have recalculated the orbital elements of Mira A-B with Kowalsky (1873)'s analytical method and obtained (as announced in the *IAU Commission 26 Inf. Circ. No 145*):

node	=	138.8	(2000)
omega	=	258.3	
i	=	112.0	A = -0.07123
e	=	0.160	B = -0.32766
T	=	2285.747	F = -0.62946
P	=	497.9	G = 0.47028
n	=	0.72307	
a	=	0.800	

Using the Hipparcos parallax of 0".00779, the sum of the masses of the system corresponding to this orbit is 4.4 $M_\odot$ while the semi-major axis is 102.7 A.U.. This value for the total mass of the system is reasonable, especially since only a small part of the orbit has been measured.

The orbit that we have computed is only preliminary, since the companion has only moved along a 22-degree arc. This means that the elements may significantly change in the future. For the sum of the masses, we give the value obtained when applying Kepler 3rd law to our orbit elements and Hipparcos parallax. The value of 4.4 $M_\odot$ is not unlikely since the *o* Ceti system is composed by two stars of spectral types M7III and dwarf Be (Yamashita and Maehara, 1977). With mass values of 2.5 $M_\odot$ for a M7III star (Strazys and Kuriliene, 1981) and 0.6 $M_\odot$ for a typical dwarf star (Weidemann, 1990), the total mass of the system would be 3.1 $M_\odot$. Hence the value of 4.4 $M_\odot$ that we have obtained is not very large, especially when the uncertainties of our elements are taken into account. As a comparison, with Baize's (1980) elements, the total mass was 8.1 $M_\odot$.

Note also that the values we derived for the masses rely on the Hipparcos parallax measurement 0"007790±.00107 whose uncertainty is 13.7% which means it is reasonably reliable. As a comparison, the parallax value used by Reimers and Cassatella was 0"013±0.005 (Jenkins, 1952), whereas the value given in the Fourth General Catalogue of Trigonometric Stellar Parallaxes (Van Altena et al. 1995) was 0"0230±0.0055.

In our opinion, this orbit remains undetermined (grade 5), although it could be considered as preliminary (grade 4) according to the definition given in Heintz-Worley's catalogue. It should be valid for the next 10 years or so (see ephemerids in Table 3).

Table 3: Ephemerides for the revised orbit of Mira A-B

Epoch	ρ_C (arcsec)	θ_C (deg.)
2001.0	0.556	106.7
2002.0	0.551	106.1
2003.0	0.545	105.6
2004.0	0.540	105.0
2005.0	0.535	104.4
2006.0	0.530	103.8
2007.0	0.525	103.2
2008.0	0.520	102.5
2009.0	0.515	101.9
2010.0	0.510	101.2

7. Conclusion

Our observations of the binary system Mira A-B have provided astrometry and photometry measurements, and restored images in full agreement with HST measurements made at the same epoch (Karovska et al., 1997). This confirms the validity of ground-based observa-

Table 4. $O-C$ residuals for the revised orbit of Mira A-B

Year	ρ_O	ρ_C	$\Delta\rho_{O-C}$	θ_0	θ_C	$\Delta\theta_{O-C}$
1923.840	0.910	0.816	0.094	130.542	133.472	-2.930
1923.899	0.900	0.816	0.084	133.642	133.457	0.185
1923.900	—	0.816	—	133.242	133.457	-0.215
1924.496	0.850	0.816	0.034	135.640	133.304	2.336
1924.671	0.910	0.816	0.094	134.340	133.259	1.081
1924.690	0.840	0.816	0.024	131.840	133.254	-1.414
1925.560	0.780	0.815	-0.035	129.137	133.030	-3.893
1929.050	0.650	0.812	-0.162	128.626	132.129	-3.503
1929.060	0.750	0.812	-0.062	131.226	132.126	-0.900
1929.980	0.850	0.811	0.039	134.923	131.887	3.036
1929.980	0.650	0.811	-0.161	133.523	131.887	1.636
1930.170	0.850	0.811	0.039	133.122	131.838	1.284
1931.260	0.820	0.810	0.010	131.219	131.554	-0.335
1931.410	0.790	0.810	-0.020	129.218	131.514	-2.296
1932.000	0.840	0.809	0.031	129.916	131.360	-1.444
1933.810	0.790	0.806	-0.016	130.611	130.885	-0.274
1935.720	0.850	0.803	0.047	131.005	130.381	0.624
1939.090	0.870	0.797	0.073	131.294	129.481	1.813
1940.380	0.890	0.795	0.095	129.890	129.133	0.757
1941.910	0.860	0.792	0.068	130.285	128.716	1.569
1943.770	0.790	0.787	0.003	130.579	128.206	2.373
1945.820	0.840	0.783	0.057	130.772	127.637	3.135
1951.020	0.790	0.769	0.021	128.656	126.158	2.498
1952.990	0.730	0.763	-0.033	125.050	125.583	-0.533
1953.880	0.780	0.760	0.020	124.247	125.321	-1.074
1954.780	0.620	0.757	-0.137	124.444	125.053	-0.609
1954.960	0.680	0.757	-0.077	121.143	125.000	-3.857
1955.780	0.650	0.754	-0.104	120.541	124.754	-4.213
1957.580	0.670	0.748	-0.078	124.535	124.208	0.327
1957.600	0.550	0.748	-0.198	121.635	124.202	-2.567
1957.610	0.560	0.748	-0.188	124.435	124.199	0.236
1959.930	0.570	0.740	-0.170	123.228	123.482	-0.254
1960.020	0.650	0.740	-0.090	117.027	123.454	-6.427
1961.030	0.760	0.736	0.024	124.724	123.137	1.587
1961.070	0.740	0.736	0.004	123.424	123.124	0.300
1961.940	0.710	0.733	-0.023	125.221	122.848	2.373
1962.080	0.650	0.733	-0.083	119.221	122.804	-3.583
1962.090	0.670	0.733	-0.063	123.221	122.801	0.420
1962.390	0.670	0.731	-0.061	124.320	122.705	1.615
1962.750	0.600	0.730	-0.130	121.119	122.589	-1.470
1962.830	0.680	0.730	-0.050	125.418	122.564	2.854
1962.890	0.720	0.730	-0.010	124.618	122.544	2.074
1962.960	0.610	0.729	-0.119	123.618	122.522	1.096
1963.971	0.560	0.726	-0.166	130.415	122.195	8.220
1964.300	0.790	0.724	0.066	124.014	122.088	1.926
1964.827	0.660	0.722	-0.062	123.312	121.916	1.396
1964.838	0.660	0.722	-0.062	121.512	121.912	-0.400
1965.550	0.650	0.720	-0.070	120.110	121.678	-1.568
1965.784	0.630	0.719	-0.089	121.609	121.600	0.009
1965.950	0.720	0.718	0.002	122.008	121.545	0.463
1967.760	0.570	0.711	-0.141	112.103	120.939	-8.836
1969.100	0.600	0.706	-0.106	116.698	120.482	-3.784
1971.068	0.550	0.698	-0.148	120.092	119.798	0.294
1973.036	0.740	0.689	0.051	122.486	119.097	3.389
1974.146	0.820	0.685	0.135	120.082	118.695	1.387
1974.738	0.680	0.682	-0.002	121.780	118.478	3.302
1974.773	0.800	0.682	0.118	119.280	118.465	0.815
1975.840	0.630	0.677	-0.047	118.877	118.069	0.808
1976.658	0.550	0.674	-0.124	121.874	117.763	4.111
1976.773	0.680	0.673	0.007	122.774	117.719	5.055
1976.787	0.720	0.673	0.047	122.974	117.714	5.260
1983.874	0.670	0.641	0.029	113.051	114.902	-1.851
1986.937	0.630	0.626	0.004	112.042	113.595	-1.553
1990.508	0.610	0.608	0.002	111.030	111.990	-0.960
1993.075	0.470	0.596	-0.126	116.122	110.778	5.344
1995.942	0.578	0.581	-0.003	108.313	109.362	-1.049
1995.945	0.620	0.581	0.039	108.013	109.360	-1.347
1998.657	0.570	0.568	0.002	106.004	107.954	-1.950
1998.657	0.590	0.568	0.022	110.004	107.954	2.050
1998.660	0.560	0.568	-0.008	110.004	107.954	2.050
1998.660	0.583	0.568	0.015	110.004	107.954	2.050

tions with speckle interferometry techniques both for astrometry and photometry.

Our survey of a sample of 35 late-type stars led to 6 detections of a companion. We have been able to obtain new position and relative photometry measurements for these objects that will be useful for future orbit determination. We revised the orbit of Mira A-B since our measurements were in disagreement with the most recent orbit, whose computation was done 20 years ago.

Although photometric/color variations of Mira B were reported by some observers, we did not detect such variations on a time scale in the range of 5-10 minutes. Future observations could also be performed with high accuracy photometers on the integrated light of both components for some objects of our sample.

Due to a change of policy in the attribution of telescope time at Pic du Midi, PISCO was de-commissioned in 1998 and we have been unable to continue our survey and do the follow up of the positive detections. Clearly, this long-term program should be continued and we encourage other observers to do so. It is all the more desirable since the study of these binaries is of a particular interest, as a long term perspective, (i) for mass determination since it may be possible within a human life to evaluate some orbital periods, (ii) to check whether photometric variations of the companion are a common phenomenon. Further studies of the relation between mass-loss and binarity might then become possible using a larger sample of double miras.

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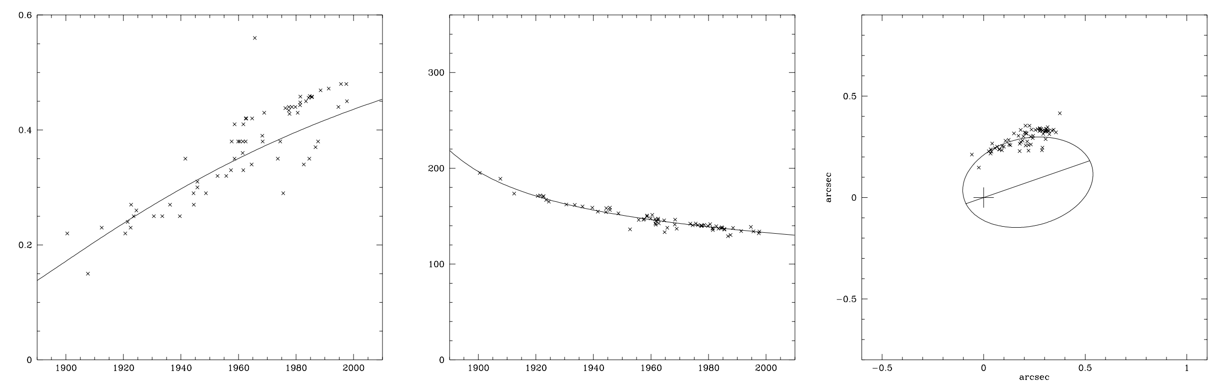

Fig. 5.— More than twenty years after its computation, Baize (1980)'s orbit of X Oph (solid line) is still satisfactory and well fits the measurements (crosses). From left to right: angular separation (ρ in arcseconds vs epoch of observation), position angle (θ in degrees vs epoch of observation), and relative motion in the plane of the sky (North to the bottom, East to the right).

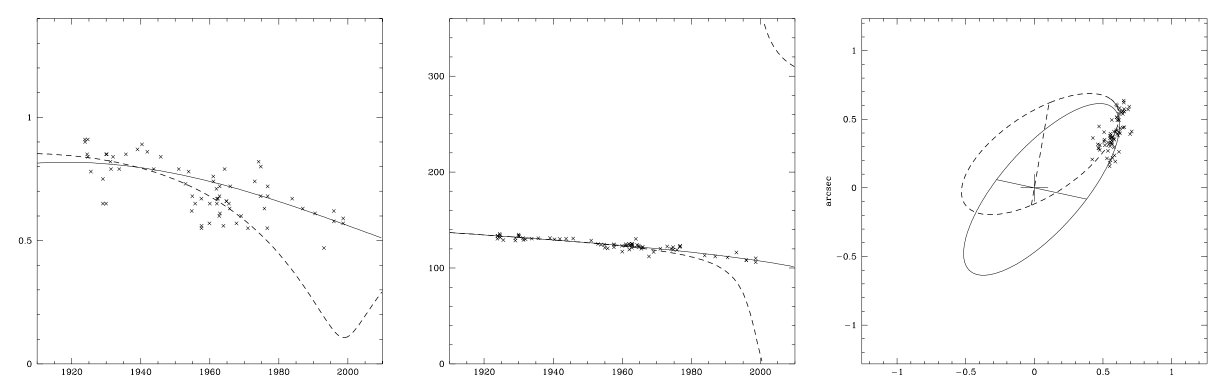

Fig. 6.— New orbit proposed for Mira A-B (solid line) and measurements (crosses). Baize (1980)'s orbit (dashed line) was not valid any longer. From left to right: angular separation, position angle, and relative motion in the plane of the sky (same as Fig. 5).