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Research Note

The distance to eight X-ray sources derived from Hipparcos observations

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Abstract. The parallaxes of eight galactic X-ray sources measured by Hipparcos are consistent with zero in all but two cases, 4U1145-619 (= Cen X-5) and HZ43. The parallax and proper motion measured for each of the others, including the Be/neutron star binaries X Per and A0535+26 and the massive X-ray binaries 4U0900-40, 4U1700-37, and Cyg XR-1, are consistent with their spectroscopic parallaxes. These results provide no evidence that visible stars in X-ray binaries have a luminosity that is abnormal for their spectral type.

Key words: astrometry – stars: distances – stars: kinematics – X-rays: stars

1. Introduction

After the initial identification of the optical counterparts of X-ray sources, it became apparent that in many cases the visible star was a binary companion of the object emitting the X-rays. The distance to these systems can be derived from the visible star's spectroscopic parallax if one makes the usual assumption that the star's luminosity is normal for its spectral type. It is possible in theory for a star with an unusual structure to mimic the type of spectrum seen in the optical counterparts, leading to an incorrect spectroscopic parallax for these systems (Wilson & Fox 1981; Bahcall et al. 1974; Trimble et al. 1973). Hence, we proposed including several optical counterparts of X-ray sources in the Hipparcos mission in order to determine whether their astrometric parallaxes were consistent with their spectroscopic parallaxes. The Hipparcos catalog (ESA 1997) includes eight of the systems we proposed. Given that six of these systems had spectroscopic parallaxes of $\sim 2\,$kpc and the nominal precision of Hipparcos parallax measurements was ~ 1 mas, we expected the measured parallaxes of these six systems to be consistent with zero.

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2. Data analysis

The Hipparcos catalogue (ESA 1997) includes measurements of the parallax, π, and the components of proper motion in right ascension and declination, μ_α and μ_δ, of 117,955 stars, together with the statistical uncertainty associated with each measurement. The total proper motion is μ = $[{\mu_\alpha}^2 + {\mu_\delta}^2]^{1/2}$ toward equatorial position angle ϕ = Arc tan($-\mu_\alpha/\mu_\delta$). We give the measured parallax and proper motion of the sources we observed in Table 1.

The equations relating (μ_α, μ_δ) to (μ, ϕ) are formally identical to those relating the Stokes parameters (q,u) to the total linear polarization (p, θ). Dolan & Tapia (1986) give the equations for the propagation of error from (μ_α, μ_δ) to (μ, ϕ) in terms of their polarimetric counterparts. The probability density functions (pdf) of the Stoke parameters and (μ_α, μ_δ) are identical, and so the pdf of polarization and proper motion measurements must also be identical. By analogy with the Stokes parameters, (μ_α and μ_δ) are normally distributed at high signal to noise ratios R = $\mu/\sigma(\mu) >> 1$, but deviate in a known way from a normal distribution at small values of R (Clarke et al. 1983). The pdf describing μ is the Rice distribution (Simmons & Stewart 1985). The pdf describing ϕ is more complicated and depends on both ϕ and μ (Naghizadeh-Khouei & Clarke 1993).

The confidence interval on the measured value of μ will just include zero at some critical significance level Cσ. The question of interest here is the significance of any particular measured proper motion, i.e., for what value of C should we accept the hypothesis that no proper motion has been measured if R $< C$? The significance criterion C is not derivable from the statistics of the pdf describing the measured variable. It is selected by the subjective judgment of the individual observer based on the confidence level one wishes to obtain. Clarke et al. (1983) show that (μ_α and μ_δ) are not well represented by a normal distribution when R $< (2-3)$. The Rice distribution becomes nearly Gaussian for R > 2 (Simmons & Stewart 1985), and all estimators of the best value of μ are consistent for R > 4. The distribution of measured values of ϕ becomes nearly Gaussian for R > 6 (Naghizadeh-Khouei & Clarke 1993). The significance level used in other fields of astronomy varies. To

Table 1. Parallax and proper motion

Hipp. #	ID	π (mas)	d (pc)	μ $(mas\ yr^{-1})$	ϕ (deg)	v_t (km s^{-1})
18350	4U0352+30/X Per	1.21 ± 0.94	> 320	4.9 ± 0.9	204 ± 5	> 7.5
26566	A0535+26/HDE245770	3.00 ± 1.72	> 150	6.7 ± 1.4	229 ± 6	> 4.9
44368	4U0900-40/HD77581	-0.38 ± 0.78	> 640	10.1 ± 0.6	325 ± 2	> 31
57569	4U1145-619/HD102567	1.98 ± 0.95	510 ± 240	6.8 ± 0.8	288 ± 4	16 ± 8
64766	HZ43	31.26 ± 8.33	32 ± 9	189 ± 8	237 ± 1	29 ± 8
82911	HD152667	-0.86 ± 0.84	> 600	0.3 ± 1.0	-	-
83499	4U1700-37/HD153919	-0.21 ± 0.86	> 580	5.1 ± 0.6	22 ± 4	> 14
98298	Cyg XR-1/HDE226868	0.58 ± 1.01	> 385	8.5 ± 0.9	207 ± 3	> 15

Table 2. Peculiar Tangential Velocities

ID	d (pc)	l	b	t (km s^{-1})
X Per	700[a]	163	-17	15 ± 3
A0535+26	$2,000$[b]	181	-3	57 ± 14
4U0900-40	$1,900$[c]	263	4	40 ± 5
4U1145-619	510 ± 240	296	0	17 ± 7
HZ43	32 ± 9	54	84	40 ± 7
HD152667	$2,000$[d]	345	2	< 38
4U1700-37	$1,700$[e]	348	2	57 ± 5
Cyg XR-1	$2,500$[f]	71	3	48 ± 10

[a] Lyubimkov et al. (1997)
[b] Steele et al. (1998)
[c] Sadakane et al. (1985)
[d] Schild et al. (1971); Crawford et al. (1971)
[e] Bolton & Herbst (1976)
[f] Margon et al. (1973)

accept a measured polarization as significantly different from zero, polarimetry uses C = 3 (the 99.7% confidence interval) (Walborn 1968; Serkowski et al. 1975; Piirola 1977); if R $<$ 3, the measured polarization is considered to be zero. X-ray astronomy uses C = 3 (Forman et al. 1978; Wood et al. 1984) for the detection of a source. Pulsar astronomy uses C > 5 (Hulse & Taylor 1974) for the detection of a pulsar. Following Sofia et al. (1969) for proper motions, we adopted the significance criterion C = 2 and assumed that no proper motion was detected if R < 2 (i.e., if the 95% confidence level included zero).

The pdf for parallax is also non-Gaussian, but can be acceptably represented by a normal distribution at larger values of R under certain reasonable assumptions (Kovalevsky 1998). Kovalevsky suggests R = 2.5 as the signal to noise ratio above which the pdf of parallax measurements can be treated as a normal distribution. For consistency, we adopted C = 2 for parallax measurements, and accepted the hypothesis that no parallax was detected if R < 2. Under this criterion, only two of the sources in Table 1, 4U1145-619 and HZ43, have measured parallaxes. The other sources have parallaxes consistent with zero, and 2σ lower limits are given for their distance.

The proper motion of each source in Table 1 except HD152667 is significantly different from zero. For the six sources for which only lower limits on the distance can be obtained from Hipparcos observations, only a lower limit on their tangential velocity, v_t, is given in Table 1.

Table 2 gives the peculiar tangential velocity, t, each source would have if it were at the distance given in Column 2. For the six sources for which no Hipparcos parallax was measured, the distances in Column 2 are estimated from spectroscopic parallax or from the distance gradient of absorption in the field (cf. the references given in Table 2). For galactic rotation we used the Oort constants A = 14.82 ± 0.84 km s^{-1} kpc^{-1} and B = -12.37 ± 0.64 km s^{-1} kpc^{-1} derived by Feast & Whitelock (1997) from Hipparcos observations of Galactic Cepheids. For the solar motion we used (U_0, V_0, W_0) = (11, 15, 7) ± 2 km s^{-1} (Jaschek & Valbousquet 1994, 1993). The uncertainty in t includes no contribution from the uncertainty in the distance for any sources except 4U1145-619 and HZ43. The peculiar tangential velocity given for HD152667 is a 2σ upper limit at a distance of 2 kpc.

3. Results

3.1. OB supergiants

4U0900-40/HD77581, 4U1700-37/HD153919, Cyg XR-1/HDE226868, and HD152667 are all binary systems with an OB supergiant primary (Dolan & Tapia 1988; 1984; 1989). No member of this group has a measurable parallax (Table 1). If each of these systems is at a distance consistent with its spectroscopic parallax, then 4U0900-40, 4U1700-37 and Cyg XR-1 have peculiar tangential velocities t > 40 km s^{-1}, while the 2σ upper limit on the peculiar tangential velocity of HD152667 is t < 38 km s^{-1}. The major difference between these systems is that 4U0900-40, 4U1700-37 and Cyg XR-1 have a collapsed secondary, while HD152667 apparently does not (Dolan & Tapia 1984). The commonly accepted evolutionary path of neutron stars and black holes in binary systems requires them to be formed in a supernova event (Canal et al. 1990). If the event occurs in a binary system that remains bound afterwards, then a large space velocity of the system, generally defined to be > 30 km s^{-1}, should result (Blaauw 1961; Hills 1983). Each system's peculiar tangential velocity agrees with this prediction of the Blaauw scenario: the three systems with a secondary formed in a supernova event have a large peculiar tangential velocity, while the system without such a secondary does not.

If we locate 4U0900-40 at its spectroscopic-parallax distance, then the peculiar tangential velocity we derive from its proper motion as measured by Hipparcos (40 ± 5 km s^{-1}) agrees both in magnitude and direction with that derived by Kaper et al. (1997a) from observations of the bow shock wave caused by the motion of the system through the interstellar medium. Kaper et al. (1997b) estimate a space velocity of 50 $\mathrm{km\,s^{-1}}$ (no uncertainty stated) for 4U0900-40 relative to the velocity of the nearby Vel OB1 association.

3.2. Be/X-ray sources

Three of the sources in our sample, X Per, A0535 +26/HDE245770, and 4U1145-619(= Cen X-5)/HD102567, are X-ray binary systems with Be star primaries. In each case, a compact secondary is the X-ray source (Dolan et al. 1998). 4U1145-619 has a measured parallax that is significant at the 2σ level (Table 1). Only a lower limit to the distance to X Per and A0535+26 can be obtained from the Hipparcos observations.

Chevalier & Ilovaisky (1998, hereafter CI) included all three sources in a survey of 13 Be/X-ray binary systems. CI found a distance of 830 (+2870, -330) pc to X Per, 330 (+450, -120) pc to A0535+26, and 500 (+500, -200) pc to 4U1145-619. These distances are consistent with the distance we find for 4U1145-619 and the lower limits we find for X Per and A0535+26. CI interpret the Hipparcos results for A0535+26 and X Per as measurements of their parallax because they apparently selected a significance criterion C $\leq$ 1.3. (The Hipparcos parallax measurements for these two sources have R = 1.3 and 1.7, respectively.)

The distances CI derive for several Be/X-ray binary systems are significantly smaller than the previously accepted spectroscopic-parallax distances for these systems. CI concluded that Be/X-ray binaries are relatively nearby, low-velocity systems (d < 1 kpc, t $< 20\,\mathrm{km\,s^{-1}}$). Steele et al. (1998) and Neguerela (1998) disagreed with the distances CI derived to A0535+26 and LSI +61°303, and argued from other lines of evidence that the larger spectroscopic-parallax distance to these systems was correct. Our interpretation of the Hipparcos parallax results as lower limits allows the astrometric distances to X Per and A0535+26 to be consistent with the spectroscopic-parallax distances.

The 90% (1.6σ) confidence interval on the Hipparcos parallax measurement of 4U1145-619 extends to 0.43 arcsec, which corresponds to a distance of 2.3 kpc. (The best estimate of its distance given in Table 1 is 510 ± 240 pc. The uncertainty on the best estimate means that if the measurement were repeated many times using the same technique, the distribution of the values obtained for the best estimate would lie in the range 120 pc to 900 pc 90% of the time.) Neguerela (1998) gives an estimate of 3.1 kpc (no uncertainty stated) for the spectroscopic-parallax distance of 4U1145-619. The distance ranges corresponding to the 90% confidence intervals on the spectroscopic and astrometric parallaxes of 4U1145-619 probably overlap.

3.3. HZ43

The hot DA white dwarf HZ43 (Margon et al. 1976), a soft X-ray source and high proper motion spectroscopic binary, was included in the trigonometric parallax program of the U. S. Naval Observatory. Dahn et al. (1982) found the system's parallax to be 15.5 ± 3.4 mas and its proper motion 176 ± 2 mas yr^{-1} toward 235.8°$\pm 0.5°$. The Hipparcos and USNO parallaxes differ by 1.8 times their the combined standard error, which is not significantly different under the criterion C = 2. The proper motions are consistent with each other.

4. Conclusions

Using the criterion that no parallax has been detected if its derived value is less than twice its statistical uncertainty, we find that the Hipparcos parallaxes of the four massive X-ray binaries and three Be/X-ray binaries in our sample are consistent with their previously accepted spectroscopic-parallax distances. The Hipparcos proper motions of the binaries with OB supergiants correspond to peculiar tangential velocities at their spectroscopic-parallax distances which are in agreement with the predictions of the Blaauw mechanism. The results provide no support for the existence of a visible component in any of these systems with a stellar structure not normal for its spectral type.

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