A REVISED PARALLAX AND ITS IMPLICATIONS FOR RX J185635−3754

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ABSTRACT

New astrometric analysis of four Wide Field Planetary Camera 2 images of the isolated neutron star RX J185635−3754 shows that its distance is 117 ± 12 pc, nearly double the originally published distance. We argue that the star’s birthplace was in the Upper Scorpius association but that a connection with ξ Ophiuchi is now unlikely. Assuming birth in Upper Sco, the revised distance yields an age of 5 × 10⁷ yr and a space velocity of about 185 km s⁻¹. The radiation radius inferred from fitting the full spectral energy distribution lies between 12 and 26 km, with a best fit $R_\ast = 16.4 \pm 0.3$ km for a two-blackbody model. These radii are in the range of many equations of state, both with and without exotic matter, and remove the observational support for an extremely soft equation of state.

Subject headings: open clusters and associations: individual (Sco-Cen Association) — stars: individual (RX J185635−3754) — stars: kinematics — stars: neutron

1. INTRODUCTION

The compact object RX J185635−3754 (Walter, Wolk, & Neuhauser 1996; Walter & Matthews 1997) is one of the closest isolated neutron stars to the Sun (Walter 2001). Because of its relative brightness, its isolated nature, and its apparently thermal spectrum from X-ray to optical wavelengths, this object affords us the opportunity to study the surface properties of neutron stars and to measure its radius. These are important constraints on the dense matter equation of state and on the interior composition of the neutron star. The angular diameter has been estimated by modeling of the spectral energy distribution (e.g., Pons et al. 2002), while the distance is inferred from the trigonometric parallax.

Walter (2001) found a parallax of 16.5 ± 2.3 mas, based on three images obtained with the Hubble Space Telescope (HST) Wide Field Planetary Camera 2 (WFPC2). The implications of the inferred 61 pc distance include a likely origin in the Upper Scorpius OB association, possibly as a companion to the run-away O star ξ Ophiuchi, an age of 0.9 × 10⁶ yr, and a space velocity of about 100 km s⁻¹. The uniform-temperature, non-magnetic heavy-element atmospheric model fits of Pons et al. (2002) implied a radiation radius $R_\ast = R/(1 - 2GM/c^2)^{1/2} \approx 6-8(D/61) \text{pc}$ and a redshift $z = (1 - 2GM/Rc^2)^{1/2} - 1 \approx 0.3-0.5$, where $M$ and $R$ are the neutron star’s mass and radius, respectively. The indicated radii and masses are in the ranges of 4.5–8 km and 0.6–1.2 $M_\odot$, respectively, and, collectively, were smaller than allowed by any reasonable equation of state, including that of self-bound strange quark matter. Relaxing the assumption of uniform surface temperature, Pons et al. (2002) showed that radii up to $R_\ast = 13$ km could be accommodated.

Kaplan, van Kerkwijk, & Anderson (2002) reexamined the WFPC2 images, using a more sophisticated point-spread function–fitting technique to measure source positions and improved (and unpublished) geometric distortion corrections. They concluded that the parallax is $7 ± 2$ mas, resulting in a distance about twice what Walter (2001) measured. As noted by Kaplan et al. (2002), at this distance the masses and radii inferred by Pons et al. (2002) would then be in agreement with conventional equations of state.

New, high-resolution X-ray spectra (Burwitz et al. 2001; Drake et al. 2002) failed to detect the lines or edges predicted from nonmagnetized heavy-element atmospheres. The radius inferred from the blackbody fit to the X-ray spectrum is 5.2(D/140 pc) km (Burwitz et al. 2001). This, together with the lack of strong pulsations (Ransom, Gaensler, & Slane 2002; Drake et al. 2002), has led to speculation that the object might be a self-bound quark star (e.g., Xu 2002; Slane 2002; Drake et al. 2002). The purpose of this Letter is twofold: to reexamine the parallax and to demonstrate that a single blackbody fit greatly underestimates the radius of the object.

2. THE DATA

Three observations are the minimum required to measure a parallax. Since the expected parallax corresponds to a subpixel shift in the PC camera (45.5 mas pixel⁻¹), we sought and were awarded a fourth observation, which occurred on 2001 March 25, in order to confirm the parallax. As with the others, the fourth WFPC2 image was scheduled near the time of maximum parallactic displacement, March 30 in this case. The earlier WFPC2 observations are described by Walter & Matthews (1997) and Walter (2001). The fourth observation, root name U62501, consists of six exposures totalling 7400 s, taken at two dither positions with nominal offsets of 5.5 pixels along each axis. The nominal pointing position was the same as in all of the other observations. The F606W filter was used to maximize the number of astrometric comparison stars. We used the same filter and pointing position to minimize differential instrumental distortions. The spectrophotometry has been discussed by Pons et al. (2002).

3. DATA ANALYSIS

We reanalyzed the images obtained at all four epochs, taking into account corrections discussed by Kaplan et al. (2002). We made no attempt to perform absolute astrometry. All positions are measured with respect to the first epoch (1996.7). The images were redownloaded from the Multimission Archive at STScI (MAST) prior to analysis to ensure that the best instrumental calibrations were applied using the MAST on-the-fly-calibration facility. We employed two independent measurement techniques and three independent analysis techniques.
3.1. Measurement of Source Positions

The first measurement of the source positions was performed by co-adding and median-filtering the data obtained at each dither point, resulting in two images per epoch. We did not analyze the individual images, primarily because of signal-to-noise ratio considerations. We fitted the positions of the targets in each pair of images with a two-dimensional Lorentzian function, taking into account the noise ratio considerations. We fitted the positions of the targets in each pair of images with a two-dimensional Lorentzian function as a template (using the IDL MPFIT2DPEAK function). We corrected the raw Y-positions for the 34th row error, using the prescription in Anderson & King (1999), and then applied the geometric distortion correction from Holtzman et al. (1995).

Uncertainties in the positions are the formal 1σ uncertainties of the fit parameters, based on counting statistics in the images. To these uncertainties, we added in quadrature an uncertainty of 0.03 pixels to account for systematic effects of nonuniformities in the intrapixel response. For the subsequent analysis, we used the same reference objects (mostly field stars) as employed in Walter (2001), except that stars 109, 121, 125, and 126 were removed because of difficulties in fitting their positions.

In the second measurement method, we used the HSTphot software (Dolphin 2000). This code fits point-spread functions generated with the TinyTim (Krist 1993) software. We fitted all the images from each observation, at both dither positions, simultaneously. Dolphin (2000) claims an astrometric accuracy of 0.03 pixels with this software. The HSTphot astrometry corrects for the 34th row error but does not account for the geometric distortions, for which we applied the Holtzman et al. (1995) correction. We followed all the processing steps described in the HSTphot manual prior to running HSTphot. HSTphot confirms that the objects identified as extended in Table 2 of Walter (2001) are indeed extended; all other objects are consistent with point sources. We did not include the extended objects 104, 108, or 109 in this analysis.

3.2. Analysis of the Source Positions

We analyzed the measured positions by three independent methods. The derived proper motions and parallaxes are presented in Table 1.

3.2.1. Full Astrometric Solution

First, we performed full χ²-minimizations for the proper motions and parallaxes of the objects in the field, including image offsets, residual rotations from the nominal roll angles, and scale factor changes from the nominal plate scale (45.5 mas pixel⁻¹). We first attempted the full solution for all objects, giving all objects, including the neutron star, equal weight. The proper motion of the neutron star, which greatly exceeds that of all other objects, caused the results to be skewed. About 3% of the proper motion of the neutron star went into the plate offsets.

We then solved for the image offsets, residual rotations, and scale factor changes using only the field objects. The net parallax and proper motions of the field objects is insignificant. We verified that neglecting the parallaxes and proper motions of the field stars yielded nearly identical results. The results quoted in Table 1 are from this hybrid analysis, using the plate solution derived in the absence of the neutron star. Uncertainties are determined by inverting the correlation matrix.

3.2.2. Independent X, Y-Regressions

Second, we determined the proper motion and parallax of the neutron star independently in the north-south and east-west directions. We registered the images with the assumption that the mean proper motions and parallaxes of the field stars are negligible. We rotated the measured positions to an equatorial coordinate frame using the nominal roll angles. We registered the images by shifting by the median offset in each coordinate. We iterated the registration, excluding stars whose residual differences are significant at greater than 3σ significance. Registration using a weighted mean shift produced insignificant differences. We then determined the deviations from the nominal roll angle and plate scale by minimizing the differences between the positions at each epoch and those of the first epoch.

After resetting the roll angles and the plate scales, we reregistered the images. Uncertainties in the image registrations are about 0.02 pixels (1 mas) in each coordinate.

We then shifted the measured position of the neutron star by the plate offsets, residual rotations, and plate scale changes. The parallax vector was determined by independent linear regression in both right ascension and declination. The parallax is the projection of this vector in the direction of the parallactic motion (with a position angle of 83°).

In both the independent X, Y-regressions and the full astrometric solution, we find that the differences from the nominal rotation (<0.02) and plate scale (<0.03%) are small but significant. These affect the determination of the parallax at about the 20% level.

3.2.3. Proper Motions from Annual Pairs

As a safety check, we also determined the proper motions of all objects using the pairs of observations separated by integral years. The residuals at the half-year intervals are the sum of the parallactic shift and the measurement errors. We found residual shifts in right ascension consistent with the parallax of the neutron star determined in the other analyses, but no significant residual shift in declination. The motions determined in this measurement are fully consistent with those in Table 1, but with uncertainties about a factor of 3 larger.

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1 See http://astrog.physics.wisc.edu/~craigm/idl/fitting.html.
4. DISCUSSION AND ASTROPHYSICAL IMPLICATIONS

The various techniques yield the same results within the uncertainties and are presented in Table 1. For the subsequent discussion, we use the 117 ± 12 pc distance obtained with full least-squares minimization using the HSTphot positions, which have slightly smaller nominal errors than those of the two-dimensional fits. This result is robust because it is based on four observations, two at each apex of the parallactic ellipse. We attribute the difference between this distance and the 61 pc distance (Walter 2001) to the inadvertent neglect of the geometric distortion of the camera. The revised parallax is slightly larger than, but agrees to within errors with, that reported by Kaplan et al. (2002).

We examined all the stars in the field for their proper motions and parallaxes. The mean proper motions in (X, Y) are (-1, 2) × 10^{-5} mas yr^{-1}, respectively, and the mean parallax is 4 × 10^{-6} mas. This justifies the assumptions used for the image registration in § 3.2.2.

4.1. Origin and Age

Walter (2001) suggested that RX J185635−3754 had its origin in the Upper Scorpius OB association. This conclusion is unaltered by the present analysis. The proper motion is essentially unchanged from what was originally reported, but the tangential space velocity is revised to 185(D/117 pc) km s^{-1}. For radial velocities larger than −150 km s^{-1}, the projected path of the neutron star traverses the projected position of the Upper Scorpius OB association within the last 2 million years.

If the neutron star originated in Upper Sco, then the distance of closest approach of the neutron star to the center of the association is a function of the assumed radial velocity. For a present distance of 117 pc, the smallest separation of the star from the center of the association is about 8.1 ± 2.9 pc, which occurs for an assumed radial velocity of 0 km s^{-1} (at the ±1σ distances, the radial velocity that results in closest approach ranges from −20 to +30 km s^{-1}). The closest approach occurred in this case about 0.5 million years ago. This separation is appreciably smaller than the size of the association, presently 14′ (de Zeeuw et al. 1999), even after accounting for the expansion of the association with time. The range in radial velocities that brings the star within the observed cluster radius is about ±30 km s^{-1}. If the radial velocity is assumed to be no larger than 0.7 of the tangential velocity, then the likelihood that this star passed through the Upper Sco cluster within the last 2 Myr is between 20% and 25%.

If RX J185635−3754 was born in the Upper Sco association and its age is 5 × 10^{5} yr, it is no longer a viable candidate for the binary companion of the runaway O star ζ Oph. Hoogerwerf, de Bruijne, & de Zeeuw (2001) argue that the pulsar PSR J1932+1059 is the likely companion. Either RX J185635−3754 is the result of a more recent supernova or it is unrelated to the Upper Sco association.

The conclusion of Pons et al. (2002) that RX J185635−3754 is, within uncertainties, on the standard cooling curve expected for neutron stars is unaltered because the smaller revised age is compensated by the increased luminosity at the larger distance. The intrinsic luminosity of the two-component blackbody model described in the next section is 7.5 × 10^{31} ergs s^{-1} at a distance of 117 pc; the unabsorbed luminosity of the best-fit single-temperature blackbody to the X-ray data alone is 4.7 × 10^{31} ergs s^{-1}.

4.2. The Radius

The most important reason to measure an accurate distance to this neutron star is to constrain its mass and radius. As first noted by Walter et al. (1996), the blackbody fit to this object results in a radius of only a few kilometers. Recently, high-resolution Chandra X-ray spectra have become available. Burwitz et al. (2001) and Drake et al. (2002) find that the Chandra X-ray spectrum is consistent with a blackbody temperature of 63 eV and that there is no evidence of the absorption lines and edges expected from a nonmagnetized heavy-element atmosphere. The Chandra spectrum yields a higher blackbody temperature than did the ROSAT data and consequently requires a smaller angular diameter (R/ID = 0.037 ± 0.001 km pc^{-1}; Burwitz et al. 2001) for the X-ray-emitting surface. At the revised distance, R_\odot = 4.3 km. On this basis, together with the featureless spectrum and lack of significant pulsations, Drake et al. (2002) suggested that the object may be a self-bound quark star.

However, as demonstrated by Pons et al. (2002), and earlier by Pavlov et al. (1996) and by Rajagopal & Romani (1996), the inferred radius depends critically on the details of the atmosphere and the spectral energy distribution. Comparing the ROSAT and Extreme Ultraviolet Explorer (EUVE) X-ray observations with optical and ultraviolet data, Pons et al. (2002) showed that the optical and ultraviolet radiation cannot originate from the X-ray blackbody (see Fig. 1). Either the X-ray emission arises in a hot polar cap or there is significant modification of the spectral energy distribution from radiative transfer through a stellar atmosphere.

If the surface has two different thermal components, we can follow the formalism of Pons et al. (2002) to estimate the true radius. Extrapolation of the 63 eV blackbody fit to the Chandra spectrum underpredicts the optical flux by a factor of 7 (Fig. 1). Attribution of the optical flux to the cooler part of a two-temperature blackbody surface results in R/ID < 0.22 km pc^{-1}, for a radiation radius R_\odot < 26 km at a distance of 117 pc. This
upper limit is for the coolest acceptable component, with $kT = 15$ eV (Pons et al. 2002); the formal best fit (see Fig. 1) has $kT = 30$ eV and $R_\ast = 16.4 \pm 0.3$ km.

In reality, the situation is likely to be more complex than a simple one- or two-component blackbody: stars have atmospheres. Pons et al. (2002) showed that the full spectral energy distribution of the neutron star, from optical to X-ray wavelengths, could be reproduced by single-temperature, nonmagnetic heavy-element atmospheres. The radii inferred from these models are significantly larger than one would get from a blackbody fit to the X-rays alone and are similar to those obtained from the two-component blackbody fit described above.

It might seem that the lack of spectral features in the Chandra spectrum invalidates much of the work of Pons et al. (2002) since nonmagnetized heavy-element atmosphere will have strong absorption lines and edges. However, it remains true that the gross spectral energy distribution is well fitted by this kind of an atmospheric model. It may be possible to dilute spectral features by changing the composition (especially by reducing the Fe and Ni content), through pressure effects, and as a consequence of the expected strong magnetic fields. The nonmagnetic models are still likely to be illustrative of the redistributive effects of the atmosphere on the full spectral energy distribution. The inferred radii from the nonmagnetic Fe and Si-ash atmospheric fits at the revised distance are consistent with canonical neutron star values; at $117 \pm 12$ pc, $R_\ast = 15 \pm 3$ km, $R = 11.4 \pm 2$ km, $M = 1.7 \pm 0.4$ $M_\odot$, and the redshift $z = 0.35 \pm 0.15$. These values are permitted by a large number of current equations of state (Lattimer & Prakash 2001), including those containing exotic matter such as quarks in their cores (see Fig. 2).

We are examining model atmosphere fits to the Chandra spectrum as well as to the full multiwavelength spectral energy distribution (work in progress). Pons et al. (2002) analyzed only nonmagnetic model atmospheres. New generations of magnetic model atmospheres are becoming available and may be able to better reproduce the observed spectral energy distribution as well as the lack of significant spectral features and pulsations. Since we cannot yet select which atmospheric model best represents the full spectral energy distribution, the radius inferred from blackbody fits to the X-rays alone represents no more than lower limits to the true radiation radius.

The apparent disagreement between the Chandra and ROSAT spectral fits (Burwitz et al. 2001) suggests that there may be unresolved calibration issues that affect our ability to determine the radius at the level needed to distinguish various equations of state. Until we understand the full spectral energy distribution, it is premature to infer that the radius is substantially smaller than that expected from a normal neutron star.

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