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THE 3U 0900−40 BINARY SYSTEM: ORBITAL ELEMENTS AND MASSES

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ABSTRACT

Observations of the 283 s X-ray pulsations from 3U 0900−40 (=Vela X-1) over a 36 day interval have led to a determination of the orbital elements for the X-ray star. These elements yield an X-ray mass function $f(M) = 18.5 \pm 0.8\ M_\odot$ and, when combined with the results of optical studies of the companion star HD 77581, give a probable lower limit of 1.4 $M_\odot$ to the mass of the X-ray star.
Subject headings: stars: binaries — stars: neutron — X-rays: sources

I. INTRODUCTION

In the preceding *Letter* (McClintock *et al.* 1976, hereafter referred to as Paper I), the discovery of X-ray pulsations from 3U 0900−40 (Vela X-1) is reported. This X-ray source is in an eclipsing binary system with the optical companion HD 77581 (Hiltner 1973). The existence of X-ray pulsations with a stable pulse period of ∼283 s allows a determination of the orbit of the X-ray star from the periodic variations in the pulse arrival times. In effect, we can treat the system as a double-lined "spectroscopic" binary. In this *Letter*, we derive the orbital elements of the X-ray star, place constraints on the masses of the X-ray and optical stars, and discuss the theoretical consequences of the results.

II. THE DATA

The timing data on 3U 0900−40 were obtained from pointed observations with the SAS-3 X-ray satellite during the periods 1975 June 18.8–24.2 and July 19.3–25.3 (UT). The X-ray detectors and some details of the data acquisition are described in Paper I. We folded the counting rate data from each of 35 satellite orbits into the 282.9 s pulse period and thereby utilized all the available photon statistics to determine the arrival time of a fiducial feature on the pulse profile. We chose this feature to be the minimum at pulse phase 0.0, as shown in Figure 1 of Paper I. We thus obtained 35 arrival times of "clock ticks" from 3U 0900−40 which have a statistical uncertainty of ∼5 s. Each of these arrival times was corrected for time delay with respect to the center of the Sun. A listing of the arrival times and their uncertainties is given in Table 1.

It was evident from an initial inspection of the pulse arrival times that a constant apparent period would not fit the data. As shown below, this lack of constancy results from the Doppler delays as the X-ray source traverses its orbit about the companion star.

III. ORBITAL PARAMETERS AND MASSES

We carried out a minimum χ^2 fit of a theoretical Doppler curve with orbital eccentricity to the 35 observations of pulse arrival time in 1975 June and July. In performing the fit, we weighted the observations by the relative accuracy of each time measurement (Table 1). The theoretical curve had six free parameters: the

TABLE 1

HELIOCENTRIC ARRIVAL TIMES OF THE 283 s X-RAY PULSES

Observation Number	Sequential Number of the Pulse	Julian Date (2,442,000+)	Relative Uncertainty (arbitrary units)*
1	1	582.400650	1.0
2	22	582.469518	1.0
3	46	582.548065	1.7
4	323	583.455810	1.0
5	405	583.724499	2.5
6	1507	587.331506	1.0
7	1536	587.426377	1.7
8	1633	587.743739	1.0
9	9298	612.842117	1.0
10†	9336	612.966562	1.7
11	9386	613.129937	1.7
12	9417	613.231496	1.0
13†	9599	613.826762	1.0
14	9637	613.951037	1.0
15†	9678	614.085229	1.0
16†	9718	614.216017	1.0
17†	9759	614.350147	2.0
18	9818	614.543141	1.0
19†	9860	614.680578	1.0
20†	9897	614.801645	1.7
21	10000	615.138605	1.7
22	10052	615.308889	1.7
23	10298	616.114058	2.5
24	10342	616.258149	2.0
25	10400	616.448130	1.7
26	10441	616.582372	2.5
27	10481	616.713379	2.0
28	10557	616.978759	3.3
29	10619	617.165565	2.5
30†	10700	617.430899	1.7
31	10742	617.568409	1.0
32	10821	617.827208	2.5
33	10902	618.092654	2.5
34	11084	618.689055	2.5
35	11123	618.816867	2.5

* From the rms scatter of the residuals we deduce that 1 unit corresponds to a 1 σ uncertainty of ∼2.7 s.

† Data from these observations were used in Paper I to set upper limits on the soft X-ray flux and to produce the folded pulse profiles.

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heliocentric pulse period (P), zero-point of pulse phase, the projected orbital amplitude ($a_x \sin i$), the orbital phase, the orbital eccentricity (e), and the longitude of periastron (ω). The orbital period (P_{orb}) is not well determined by our data alone. We therefore fixed the orbital period at the value of 8ᵈ966, which is determined from optical data and is accurate to within an uncertainty of ±0ᵈ001 (Hutchings 1974). This value is also consistent with previous *Uhuru* and OSO-7 X-ray data (Forman *et al.* 1973; Li 1975).

The results of our fit are listed in Table 2. The numerical values of χ^2 were normalized such that the minimum value of χ^2, χ^2_{min}, was equal to the number of observations minus the number of free parameters. The approximate single-parameter 95 percent confidence limits ($\sim 2\ \sigma$) were then derived by projection of the $\chi^2_{min} + (2.04)^2$ error surface onto each of the parameter axes. (For discussions pertinent to this method of error estimation, see Avni 1976*a*; Lampton, Margon and Bowyer 1976; and references therein.)

The minimum χ^2 fits to circular and eccentric orbits are illustrated in Figure 1. The circular fit produces a periodic distribution of residuals with a period of $\sim P_{orb}/2$ (see Fig. 1*a*). This systematic distribution of residuals is reduced to a random scatter and the value of χ^2_{min} is reduced by a factor of ~ 2 when an eccentric orbit is used (Fig. 1*b*). The rms scatter of the residuals for the eccentric fit is 4.0 s, which is comparable to the statistical uncertainty in the arrival time of each pulse.

In a separate minimum χ^2 fit, we allowed P_{orb} to be a free parameter. We obtained P_{orb} = 8ᵈ962 ± 0ᵈ007 (1 σ), which is consistent with the value used above. In another separate fit, we allowed a constant intrinsic rate of change of pulse period ($\dot{P}$) as a free parameter. This fit yielded a 95 percent confidence upper limit to $|\dot{P}/P|$ of 1.2×10^{-3} yr^{-1}.

From our fitted value of $a_x \sin i$, we obtain an X-ray mass function of $f(M) = 18.46 \pm 0.79\ M_\odot$ (1 σ).

The most recent spectroscopic study of the companion optical star HD 77581 yielded a projected orbital amplitude of $a_{opt} \sin i = 8.0 \pm 0.7$ lt-sec (van Paradijs *et al.* 1975*b*). We have performed our own fit to the published data of van Paradijs *et al.* using a modified version of the same computer code that was used to fit the X-ray data. The values of e and ω are best determined by the

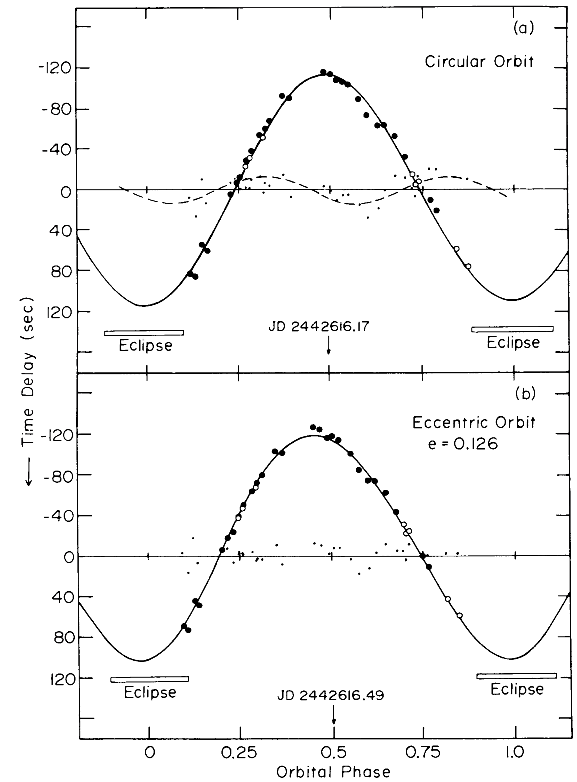

FIG. 1.—Doppler corrections to the pulse arrival times as a function of 8ᵈ966 orbital phase for (*a*) the best-fit circular orbit and (*b*) the best-fit eccentric orbit. *Open circles*, 1975 June observations; *closed circles*, 1975 July observations. The small dots are the residuals, times a factor of 2; and the solid lines are the best-fit theoretical curves. The dashed line indicates the systematic trend in the residuals of the circular orbit fit. The temporal center of the eclipse is at orbital phase 0.0, and the indicated Julian dates correspond to phase 0.5. The eclipse intervals are derived from the best-fit orbital parameters and the eclipse duration of 1ᵈ90 that was observed by Forman *et al.* (1973).

X-ray data, and P_{orb} is best determined by other optical data (Hutchings 1974). When we fix e and ω at the best-fit values in Table 2 and adopt the value of P_{orb} given by Hutchings, we obtain $a_{opt} \sin i = 7.79 \pm 0.74$ (1 σ) lt-sec. Other recent spectroscopic measurements of HD 77581 (Wallerstein 1974; Hutchings 1974; Zuiderwijk, van den Heuvel, and Hensberge 1974; van Paradijs *et al.* 1975*a;* see also Avni and Bahcall 1975) yield values of $a_{opt} \sin i$ that vary between ~ 8 and ~ 16 lt-sec.

If we adopt $a_{opt} \sin i = 7.79 \pm 0.74$ (1 σ) lt-sec as a conservative value (i.e., a value that yields the *smallest* stellar masses) and combine it with the X-ray mass function, we obtain $M_x = (1.45 \pm 0.16\ M_\odot)/\sin^3 i$ and $M_{opt} = (21.1 \pm 0.9\ M_\odot)/\sin^3 i$ (1 σ) for the masses of the X-ray and optical stars, respectively. However, we emphasize that the actual values of $a_{opt} \sin i$ and the masses may well be larger than these conservative estimates. We also note that the masses increase with decreasing orbital inclination, although the analysis of the ellipsoidal light variations of the optical star and the duration of the X-ray eclipses indicates that i is no less than $\sim 70°$ (Avni and Bahcall 1975; Avni 1976*b*).

TABLE 2

BEST-FIT PARAMETER VALUES OF THE 3U 0900−40 BINARY SYSTEM*

P =	282ˢ8916±0ˢ0004
$a_x \sin i$ =	111.4±3.3 lt-sec
K_x =	273±9 km s^{-1}
$f(M)$ =	18.5±1.6 $M_\odot$
e =	0.126±0.041
ω =	146°±23°
T_0† =	JD 2442612.01±0.12

* Quoted errors are approximate single-parameter 95% confidence limits. An orbital period of 8ᵈ966 has been assumed (see text).

† T_0 = time of temporal center of eclipse.

IV. DISCUSSION

As pointed out in Paper I, it is probable that the X-ray star is a neutron star. If it is, then the lower limit on its mass (probably greater than 1.4 $M_\odot$) virtually rules out the softer equations of state that have been proposed (see, e.g., Leung and Wang 1971) for matter densities in excess of $\sim 10^{14}$ g cm^{-3}. However, the present mass limit is entirely consistent with recent conventional nuclear-matter calculations of high-density equations of state (Malone, Johnson, and Bethe 1975; Pandharipande, Pines, and Smith 1976). In order to refine this mass limit, further measurements of optical radial velocities and a better understanding of variations in radial velocity with time and among different spectral lines are critically needed.

The possible existence of a neutron star with a mass in excess of 1.4 $M_\odot$ would prove to be important to the theory of stellar evolution and supernova formation. In the conventional picture (see, e.g., Iben 1974 and references therein), the core of an evolved star collapses to form a neutron star and a supernova event ensues when the core mass reaches the Chandrasekhar limiting mass, $M_{\rm Ch} \approx 1.4\, M_\odot$. It is uncertain whether this picture can account for the existence of a neutron star more massive than $M_{\rm Ch}$.

Future X-ray observations can greatly improve the above limit on $|\dot{P}/P|$. A large value of $|\dot{P}/P|$ ($>10^{-5}$ yr^{-1}) would constitute independent evidence that the X-ray star is in fact a rotating neutron star, because a neutron star has a small moment of inertia and could be rapidly spun up or down by accreting matter (see Lamb, Pethick, and Pines 1973). On the other hand, a small value of $|\dot{P}/P|$ ($\lesssim 10^{-5}$ yr^{-1}) would be consistent with a white dwarf model for the X-ray star.

A radius of $\gtrsim 33\, R_\odot$ is obtained for HD 77581 from the measured orbital parameters and X-ray eclipse duration of $\sim 1^{\rm d}90$ (Forman *et al.* 1973) if we assume that the stellar photosphere is the occulting surface (Fig. 2). Using this value for the radius, we can estimate the luminosity of HD 77581 and thereby obtain a direct measure of the distance to the system. For a visual magnitude of 6.9 mag (Hogg 1958), a bolometric correction of −2.8 mag (see Harris 1963), an effective temperature, T_e, of 22,500 K (Avni and Bahcall 1975 and references therein), and a visual absorption, A_V, of 2.2 mag (Hiltner, Werner and Osmer 1972), we obtain an absolute visual magnitude of $\lesssim -5.9$ mag and a distance of $\gtrsim 1.3$ kpc (cf. Hiltner, Werner and Osmer 1972; Bahcall 1975). The lower limits on the stellar radius and distance and the upper limit on the absolute visual magnitude are obtained when $i = 90°$. However, the distance estimate depends sensitively upon the uncertain values of T_e and A_V, and the absolute magnitude estimate depends sensitively upon T_e (see Mikkelsen and Wallerstein 1974; Avni and Bahcall 1975; Bahcall 1975).

The derived mass ($\gtrsim 21\, M_\odot$), radius ($\gtrsim 33\, R_\odot$), and absolute visual magnitude ($\lesssim -5.9$ mag) of HD 77581 are all consistent with the observed spectral type of B0.5 Ib (Morgan, Whitford, and Code 1955).

This system differs from the two previously known binary systems containing X-ray pulsars, Cen X-3 and Her X-1, in that the orbit is appreciably eccentric with $e \approx 0.1$. It is likely that the Cen X-3 and Her X-1 systems initially had appreciable eccentricities and that the orbits were circularized by tidal interaction (see, e.g., Wheeler, Lecar, and McKee 1975 and references therein). Further theoretical studies are required to understand why the orbit of 3U 0900−40 has not been circularized.

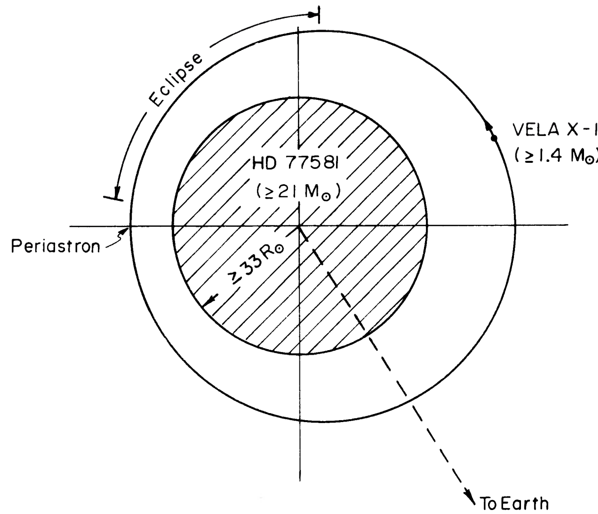

FIG. 2.—A scale drawing of the 3U 0900−40/HD 77581 binary system. The origin of the coordinate frame is at the center of the optical star. The longitude of periastron is defined such that $\omega + 90°$ is the angle from the projected line-of-sight to the Earth to the direction of the periastron point, measured in the direction of motion of the X-ray star.

The derived orbital elements of 3U 0900−40, combined with the observed eclipse duration of $1^{\rm d}90 \pm 0^{\rm d}05$ determined from *Uhuru* data (Forman *et al.* 1973), and the assumption that the stellar photosphere is the occulting surface, predict emersion from eclipse on 1975 July 19.46 ± 0.08 (UT) ($\sim 1\,\sigma$). This is only marginally consistent with the earliest posteclipse detection of 3U 0900−40 with SAS-3 on July 19.34 (UT). It is possible that the eclipse is asymmetric relative to the center of the optical star because of mass flow within the system (cf. Forman *et al.* 1973). Distortion of eclipses due to mass flow has previously been observed in the X-ray binaries Cen X-3 and 3U 1700−37 (see Avni and Bahcall 1975 and references therein).

Avni and Bahcall (1975) have analyzed the 3U 0900−40 binary system and several other X-ray binaries, using earlier optical and X-ray data. Our results lend credence to the standard theoretical picture used by Avni and Bahcall, in that the orbital velocity and mass limit that we obtain for the X-ray star in the 3U 0900−40 system fall within the ranges that Avni and Bahcall derived. This success indicates that we now have a good understanding of many of the basic optical and X-ray properties of the X-ray binary systems.

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