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A PHENOMENOLOGICAL TRIPLE STAR SCENARIO FOR SS 433

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ABSTRACT

We suggest that SS 433 is a triple star, containing a short-period ($\sim 1^{\rm d}\!.5$) binary like Sco X-1, orbiting a massive OB star in $13^{\rm d}$. Polar jets produced by the Sco X-1–like close binary can precess, with the period observed, if this binary is misaligned with the larger binary. The possible evolutionary history of such a system is discussed, starting from a triple star somewhat like either λ Tau or VV Ori.

Subject headings: stars: binaries — stars: individual

The mechanism responsible for the $164^{\rm d}$ precession of SS 433 (Margon 1984) has not yet been clearly identified. The high velocity of the opposing jets, $0.26c$, argues that they originate from a compact object (neutron star or black hole) which is most unlikely to undergo forced precession from its $13^{\rm d}\!.1$ orbital companion. Many of the more successful models proposed so far assume that the precessing object is an accretion disk surrounding the compact star (Katz 1980; Van den Heuvel, Ostriker, and Petterson 1980; Whitmore and Matese 1980). Here we outline a phenomenological model of a triple system in which an inclined close binary of period $1^{\rm d}$–$2^{\rm d}$ (cf. Sco X-1, which has a binary period of $0^{\rm d}\!.79$ and also has jets) is in a wider $13^{\rm d}\!.1$ orbit about a more massive star. The close binary then precesses in a manner similar to that of the Earth-Moon system. We suggest that such a triple system might be formed if the most massive member of a relatively unevolved triple system like VV Ori (Duerbeck 1975) explodes as a supernova, leaving a neutron star remnant, but this remnant must somehow exchange partners after its formation in order to be presently orbiting with the *least* massive component, as we postulate here.

Triple systems have been very briefly considered before as an explanation of SS 433 (Begelman *et al.* 1980; Davidson and McCray 1980; and in another context see Barker, Byrd, and O'Connell 1981). If the orbital periods of the wider and closer binaries are P_1 and P_2, and their total masses are m_1 and m_2, respectively, and if θ is the angle between the planes of the two orbits, then the precession period of the close binary is

$$P \approx \frac{4}{3}\frac{P_1^2}{P_2}\frac{m_1}{m_1 - m_2}\sec\theta\,, \qquad (1)$$

as given, for example, by Katz (1973). It is readily seen that $P_2 \approx 1^{\rm d}\!.5$ if $P = 164^{\rm d}$, and $P_1 = 13^{\rm d}\!.1$ and both θ and m_2/m_1 are assumed to be moderately small ($\theta = 20°$; Margon 1984). The X-ray binary Sco X-1 is a triple radio source (Geldzahler *et al.* 1981) of binary period $0^{\rm d}\!.79$, which presumably means that at times it emits energy in a highly collimated manner, i.e., it possesses jets. If this system were in an inclined orbit about a more massive star, then the jets would precess on a time scale of months to years. We shall not speculate here on the acceleration or collimation mechanism. There is some evidence from light curve/eclipse modeling of the optical data that the unseen companion to the observed star in SS 433 exceeds 4.3 $M_\odot$ (Leibowitz *et al.* 1984). It is this "unseen companion" that we propose to be the close binary. Mass transfer is taking place either on to or within this binary.

As in the case of the Earth-Moon system, the close binary in SS 433 undergoes more complex motions than just precession. The $6^{\rm d}\!.3$ nodding motion (Katz *et al.* 1982) is simply explained, since the same equations used by Katz *et al.* (1982) for a "slaved disk" apply to the close binary if the orbit is circular. Note, however, that a close binary would be likely to give a more coherent precession period than a differentially rotating disk. Eccentricity of both orbits might also lead to observable variations with other harmonics or periods being introduced into the data. In particular, eccentricity of the $1^{\rm d}\!.5$ orbit transfer could lead to periodic mass transfer that may be reflected in the jets. The most clear test of the model will be the detection of the orbital period of the close binary. This may not prove straightforward, since it may resemble Sco X-1, for which the underlying period was not detected until ~ 10 yr after its companion was optically identified (Gottlieb, Wright, and Liller 1975). Precession of the orbital plane of the close binary means that its orbital inclination varies. If the jets are emitted perpendicular to this plane, "eclipse seasons" occur as the jets pass 90° to our line of sight. Eclipses on the $1^{\rm d}\!.5$ period may then be observed if the companion star in the close binary is not too small or the accretion disk too thick.

The most obvious difficulty with our model is its evolution from a plausible initial configuration. Shipman (1975) has pointed to difficulties in the evolution of triple systems where one star undergoes a supernova. Since there is uncertainty about the evolutionary history of low-mass X-ray binaries (LMXBs) in general, and of Sco X-1 in particular, we perhaps need not worry about the further uncertainty of our triple model. However, we attempt to address the issue in what follows.

Most discussions of the origin of LMXBs (e.g., van den Heuvel 1981, 1983) involve either (1) an initially wide binary which shrank drastically in a "common envelope" phase, then suffered a supernova explosion in the remnant core of the original primary (van den Heuvel 1976); (2) an explosion of an accreting white dwarf in a cataclysmic binary (Canal and Schatzman 1976; Gursky 1976), this binary itself having evolved, via a common envelope, from an initially wide binary (Paczyński 1976); (3) tidal capture in a dissipative two-body near-collision of two initially independent stars (Fabian, Pringle, and Rees 1975); or (4) an exchange reaction in a non-dissipative encounter between a single neutron star and a low-mass binary (Hills 1976). Such models have been proposed

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because it is difficult (or impossible, so far) to see how a neutron star can be produced in a binary which has *always* had both a short period and a low-mass companion. Evidently the same problems confront us with even greater force in our triple-star model. We can probably exclude both (1) and (2), since they require that the $\sim 1^{\rm d}.5$ binary should have had, in the past, a separation much larger than the $13^{\rm d}.1$ orbit. But (3) or (4) may be possibilities, if suitably modified.

A possible starting point might be a triple star consisting of two massive stars in a close binary (say $2^{\rm d}$–$3^{\rm d}$) and a low-mass third star orbiting with a period several times longer ($30^{\rm d}$–$100^{\rm d}$). Two examples of such systems are

λ Tauri: ((A4 IV + B3 V, $1.9 + 7.2\ M_\odot$, $3^{\rm d}.97$) + invisible, $9.1 + 0.7\ M_\odot$, $33^{\rm d}$).

VV Ori: ((B1 V + B4 V:, $7.6 + 3.4\ M_\odot$, $1^{\rm d}.49$) + A3 V:, $11 + 1.6\ M_\odot$, $119^{\rm d}$).

The data are from Fekel and Tomkin (1982), Duerbeck (1975), and Chambliss (1984). These are the two known systems of shortest *longer* period (Fekel 1981), and the fact that λ Tauri is quite a bright star (both stars are naked-eye objects) suggests that such systems are not rare, but must be very hard to recognize. The longer period in each of λ Tau, VV Ori only shows up as a periodic motion of the center of gravity of the massive pair. Neither of these two has a component clearly massive enough to give a supernova, the lower limit for which may be $\sim 10\ M_\odot$. Note, however, that Beltrami and Galeotti (1970) and Chambliss (1984) favor substantially higher masses (by $\sim 30\%$) for VV Ori than Duerbeck (1975). Popper (1980) points to the fact that radial velocity measurements are increasingly uncertain at earlier spectral types, so it is not surprising that no O-type binary has yet been found to have a close, low-mass third companion like the two systems above. We feel that it is therefore permissible to suggest as a precursor a triple with parameters something like ((O9 V + B1 V, $15 + 10\ M_\odot$, $2^{\rm d}$) + A0 V, $25 + 2\ M_\odot$, $50^{\rm d}$).

The massive close binary which we have postulated may evolve, by mass exchange, to a presupernova binary substantially wider than the original (with $P \approx 2^{\rm d}$), but not quite so wide (with $P \approx 15^{\rm d}$) that the $50^{\rm d}$ orbit would be disrupted (Bailyn and Eggleton 1983). A supernova in the original primary (now assumed to be only 3–4 $M_\odot$) would slightly lengthen both periods, as well as making both orbits eccentric, since it would reduce the primary's mass further to a value of $\sim 1.5\ M_\odot$ apparently typical of neutron stars (Joss and Rappaport 1984). The eccentricity of both orbits, as well as their nearness to instability, will mean that the low-mass stars can have many close encounters, thus affording the opportunity for these two components to form, at least temporarily, a loosely bound system. We finally require that a small amount of tidal dissipation in this temporary binary remove sufficient relative kinetic energy to leave the low-mass pair in a long-lived, though still loosely bound, orbit; probability estimates are given below. We estimate that the $50^{\rm d}$ orbit will be reduced to $\sim 13^{\rm d}$ by this capture process (in a rather crude analogy with Roche lobe overflow, in which $1.5\ M_\odot$ is transferred conservatively from a $\sim 23\ M_\odot$ star to a $\sim 2\ M_\odot$ star). The short-period orbit of the new LMXB should have a period shorter than the maximum compatible with stability against disruption by the massive star in the $13^{\rm d}$ orbit; this is $\sim 2^{\rm d}$ (Bailyn 1983). Hence our initial estimate of $\sim 1.5^{\rm d}$ is roughly compatible with stability and with this formation hypothesis.

A variant of this model, which may actually have more chance of success, as we discuss below, starts with *four* bodies, a massive close binary and a low-mass close binary orbiting each other in a relatively wide " binary." Then by analogy with process (4) above for the creation of LMXBs, we imagine that a neutron star produced in the massive close binary is projected near to the low-mass close binary, where it in turn ejects to infinity the least massive component, leaving itself bound to the other low-mass star.

Our model requires the neutron star to transfer itself, presumably at its birth, from the companionship of the massive star to that of the low-mass third star. Several possible scenarios can be sketched, none of which, *a priori*, is very likely to occur. However, as only one SS 433 system is currently known among the $\sim 10^3$ massive stars observed in the Galaxy, we shall accept those possible evolutionary scenarios which have an *a priori* probability greater then $\sim 10^{-3}$. Our two scenarios, we believe, are likely to (1) occur with sufficient probability and (2) lead to a stable triple; unstable triples can be formed easily, but will decay under the expulsion of an unbound single star on a time scale of $\sim$ 1–100 yr (Hut and Bahcall 1983).

A zeroth, unsuccessful scenario neglects tidal dissipation. It starts with the supernova explosion being strong enough nearly to expel the massive companion, which can acquire a rather eccentric orbit, with an apastron approaching closer to the periastron of the low-mass star (which also acquires a somewhat eccentric orbit). With a small inclination between the two orbital planes, close encounters might soon occur between the neutron star and the low-mass star. A temporary exchange may well occur, as required above. However, such an exchange is never stable at long as the three stars are treated as nondissipative point masses. A simple physical argument is the time-reversability of Newton's Law, requiring an avoidance of exchange in the past as well as in the future (see Hut and Bahcall 1983): avoiding decay means avoiding formation as well. A rigorous mathematical argument is given (in the similar case where the third body comes in on a slightly hyperbolic rather than highly elliptic orbit) by Chazy (1929), who showed that stable triples are formed in this way with probability measure zero.

The first successful scenario involves a significant amount of energy dissipation during the first encounter between the neutron star and the low-mass star immediately after the SN explosion. A passage of the neutron star within two stellar radii of the low-mass star will remove and subsequently dissipate enough orbital energy ($\gg 1\%$; see Fabian *et al.* 1975) to bind these two stars. The large amount of energy dumped into the envelope of the low-mass star might complicate the analysis of subsequent periastron passages of the captured neutron star. Also, the significant perturbation by the third, massive star will continually change the periastron distance. Although a quantitative analysis might be difficult, the existence of bright X-ray sources in globular clusters give a strong hint that this kind of scenario might work. The chance of starting with an initial neutron star impact within two stellar radii of the low-mass star is of order $\sim 10^{-2}$ (taking into account gravitational focusing), well above the $\sim 10^{-3}$ required above.

The second successful scenario does not rely on the uncertain details of dissipative effects and does not necessarily require very close passages between any of the stars. Instead, we replace the single low-mass star by a close binary containing two low-mass stars. During an encounter with the neutron star, in which there is an impact parameter on the order of the separation between the two low-mass stars, there is a large probability that the heavier neutron star is captured and the lightest star expelled (see Heggie 1975). The recoil to the newly formed binary, caused by the expulsion of the lightest star, can easily cause this binary to be put into a new stable orbit around the remaining massive star. The probability for this to happen is more than 1%, as can be seen in a comparison with Mikkola's (1982) numerical experiment in which binary-binary scattering produced stable triple systems in a significant ($\sim 10\%$) fraction of his slow-encounter cases, which are comparable to the present situation.

In conclusion, it does not seem impossible that a triple system which starts as something like VV Ori may evolve into something like SS 433. The long-period orbit of the low-mass third body must start in a fairly limited range of period: if too close, the third body will be ejected by a gravitational encounter, as can be expected in λ Tau; if too wide, there is little chance that the neutron star will be ejected out of the massive binary into the neighborhood of the third body. The range of parameters in which the interaction might happen does not seem vanishingly small, provided that tidal friction is allowed for (or, alternatively, that there is yet a fourth body).

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