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Precession and System Parameters in Early-type Binary Models for SS 433

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Summary. We consider binary models in which the beams of SS 433 emerge from the center of a supercritical accretion disk around a compact object. Assuming the disk to be "slaved", i.e., its precession to be induced by driven Newtonian precession of a misaligned early-type companion star, the following constraints on the system parameters are found:

(i) if the companion's rotation is close to synchronous, only binary periods of the order of 10 d are possible;

(ii) if the companion's rotation is 1.4 to 2 times faster than synchronous, also orbital periods of the order of 10 d are allowed.

In both cases, if the compact star is a neutron star which we consider most likely, the early-type star should have a mass \( M_1 \leq -4 \) M\(_\odot\), implying, in view of its \( M_1 \leq -4 \) M\(_\odot\), that it is probably a Wolf-Rayet star. The presence of strong Balmer-line emission then implies that it is most probably a WN 7-9 star. If the compact star is an 8 M\(_\odot\) black hole, also companion masses in the range of O stars (20 M\(_\odot\) or more) are allowed. A discussion of the reported 13.1-d spectroscopic and 6.5-d photometric periodicities and their possible near 1 d and near 0.5 d aliases, respectively, shows that binary periods near 1 d, though less likely, might not yet be completely ruled out.

Key words: X-ray binaries - precession - SS 433 - accretion disks - Wolf-Rayet stars - O stars

1. Introduction

In a forthcoming paper (van den Heuvel et al., 1980; hereafter referred to as Paper II) it was argued, from the optical and IR characteristics, distance (\( \geq 3.5 \) kpc), interstellar extinction (\( A_V \geq 6 \) M\(_\odot\)) and deduced system dimensions, that the underlying optical object in SS 433 is a luminous Of- or Wolf-Rayet-like star with \( M_1 \leq -4 \) M\(_\odot\) and a stellar wind mass loss rate \( \dot{M}_w \geq 10^{-5} \) M\(_\odot\)/yr. This conjecture is further strengthened by recent radio observations (van Gorkom et al., 1980) which show the distance to be even larger than we assumed (i.e., \( 3.7 \) to \( 4.7 \) kpc), new IR observations (Giles et al., 1979; Allen, 1979) which show that the IR emission is most easily explained as \( f/f \) and \( h/f \) emission from a region of gas that has a volume, temperature and electron density very similar to those of the winds of extreme Of stars and WR stars (cf. Paper I and Sect. 4) and new determinations of the interstellar extinction which suggest \( A_V \geq 6 \) M\(_\odot\) (Murdin et al., 1980) implying \( M_1 \leq -4 \) M\(_\odot\). It was further argued in Paper I that SS 433 is likely to be a later stage of evolution of a massive X-ray binary, in which the rate of mass transfer has become supercritical, and has induced the formation of a thick accretion disk around a neutron star companion. Similar to suggestions by Katz (1980) and by Martin and Rees (1979) the beams of SS 433 are in this model thought to be due to the ejection of the excess transferred matter from the central parts of the disk, in a direction perpendicular to the disk plane. The precession of the disk and the beams is ascribed here to tidally driven (classical) precession of the misaligned rotationally deformed optical companion star. Since the transfer time of matter through the disk in massive X-ray binaries is expected to be much shorter than \( 164 \) d (cf. Bonnet-Bidaud and Van der Klis, 1979) one expects the disk to follow the precession of the companion (a so-called "slaved disk"). In this picture, W 50 is not a supernova remnant, but owes its formation to the beams of SS 433 in the way suggested by Begelman et al. (1980).

In the present paper we examine more closely the implications of the observed precession, assuming it indeed to be due to precession of the companion driven by the tidal torque on its misaligned rotational bulge. We assume the mass of the normal star to be in the range between 6 and 30 M\(_\odot\) and consider two cases, viz.:

(i) the normal star has (nearly) synchronous rotation (though misaligned), and
(ii) the normal star rotates considerably faster than synchronous. It appears that in the first case only binary periods of less than a few days are possible. This holds regardless of whether the compact star is a 1.5 M\(_\odot\) neutron star or an 8 M\(_\odot\) black hole.

On the other hand, if the star rotates some 40% faster than synchronous, tidally driven precession also allows binary periods of the order of 10 d. In the latter case, for a 1.5 M\(_\odot\) compact star the mass of the early-type component should be \( 10 \) M\(_\odot\) for an 8 M\(_\odot\) compact star there is no such restriction.

In Sect. 3 we discuss the result of Sect. 2 in the light of the recently reported 13.1-d periodicity in the radial velocity variations (Crampton et al., 1980) and the 6.5-d periodicity of the photometric variations (Kemp et al., 1980), and of their possible 1 d and 0.5 d aliases (0.5 d photometric aliases would be expected in case of a near 1 d double-wave photometric variation and appear not to be excluded by Kemp et al.'s observations, as discussed in Sect. 3).

2. Theoretical Restrictions on the Slaved-disk Model

2.1. The Synchronous Case

Assuming tidally driven precession of the non-degenerate star and using Eqs. (12)-(16) of Paper I we have

\[
P_{\text{pre}} = \frac{P_{\text{obs}} - \left( t_{\text{in}} + t_{\text{out}} \right) / t_{\text{in}}}{(R_2/a)^2 (2 a/m) (1 - e^2)^{-1/2} d / \phi},
\]

\[P_{\text{obs}}.
\]
where \( P_{\text{orb}} \) and \( P_{\text{pref}} \) are the orbital and precession period, \( m_1 \) and \( m_2 \) are the masses of the compact object and the normal star, respectively, \( R_2 \) and \( \omega_2 \) are the radius and rotational angular velocity of the normal star, respectively and \( \omega_0 \), \( a \), and \( \epsilon_2 \) are the orbital angular velocity, the semi-major axis and eccentricity of the orbit, and the apsidal motion constant of the normal star, respectively, and \( \dot{\lambda} \) is given by

\[
\dot{\lambda} = \sin(\phi + \delta) \cos(\phi + \delta) \sin \delta.
\]

(2)

where \( \delta(\phi) \) is the angle between the orbital [spin] angular momentum vector and the total angular momentum vector of the system. For \( \phi, \delta \in \pi \) (e.g., \( \leq 20 \)) we can approximate \( \dot{\lambda} \) by

\[
\dot{\lambda} \approx (\phi + \delta)/d \simeq (L + S)/S,
\]

(3)

where \( L \) and \( S \) are the absolute magnitudes of the orbital and spin angular momentum vectors, respectively (spin of the normal star). In order to estimate \( \dot{\lambda} \), one may write

\[
L/S = \left( m_1 m_2 (m_1 + m_2) \right) \omega_0 (1 - \epsilon^2)^{1/2} / k m_1 R_2 \omega_2 = \left( m_1 (m_1 + m_2) \right) (1 - \epsilon^2)^{1/2} (a/R_2) \omega_0 / \omega_2 / k \simeq
\]

(4)

where \( k \) denotes the square of the gyration radius of the normal star off the orbit above the surface. After the passage of the compact object by using an impulse-approximation. The momentum \( \dot{\lambda} \) transferred to a unit mass at the stellar surface, can be estimated from

\[
\dot{\lambda} \simeq F h / v_0.
\]

(8b)

where \( v_0 \) is the orbital velocity of the compact object in a frame corotating with the star, \( F \) is the gravitational attraction at the stellar surface, due to the compact star and \( h = a - R \) is the height of the orbit above the surface. After the passage of the compact object the surface material will fall back towards the star only if \( \dot{\lambda} < \epsilon_{\text{esc}} \), the escape velocity on the surface.

We calculated the upper limits to the stellar radius set by the centrifugal condition (8a) as well as by the impulse-condition (8b) for \( v_0 / a_0 \) ranging from 1.2 to 20, \( m_2 = 6 \) to 30, \( \omega_0 \), and \( m_1 = 1.5 \)

the upper limit by less than a factor of two, as can be seen from Table 1. If one would assume a polytropic index \( \geq 3 \), which seems still reasonable on the upper main-sequence, one obtains \( k \leq 5 \), such that the above upper limits will be reduced by about 40%. Consequently, for nearly synchronous rotation and not too large eccentricities the orbital periods allowed for driven precession in an early-type binary model are of the order of one day.

2.2. Non-synchronous Rotation

In close binaries with \( P \geq 5 \) d one often observes that the primaries rotate considerably faster than synchronous. This is particularly the case for the unevolved components of post-mass exchange binaries in which deviations of up to a factor of 5 are observed (Plavec, 1970; Olson, 1968). This is presumably due to their accretion of mass and angular momentum during the mass transfer stage. Since also the non-degenerate components of the massive X-ray binaries were originally the secondaries which went through a stage of mass accretion, non-synchronous rotation can also be expected for them.

For \( P \geq 5 \) d synchronisation by tidal forces in such systems may take longer than the lifetimes of the stars. Indeed, in the 8.96 d period massive X-ray binary 4U0900+40 (Vela X-1) still a considerable orbital eccentricity of \( \sim 0.09 \) is observed (Rappaport et al., 1980), which indicates that tidal forces have not yet been able to circularize its orbit since the supernova explosion which produced its compact star, several million years ago (cf. van den Heuvel, 1977). Since the timescales for tidal circularisation, alignment of the rotation axis and synchronisation, are of the same order, considerable deviations from synchronous rotation and alignment seem very well possible in X-ray binaries with \( P \geq 5 \) d. Misalignment may have been induced by the supernova that produced the neutron star.

In the case of large deviations from synchronisation the Roche-lobe concept becomes meaningless, and the star may become larger than this lobe without causing the onset of large scale mass transfer (cf. Taam et al., 1978). We can apply two criteria to determine the maximum stellar radius in this case.

First of all the star should not rotate so fast that it becomes centrifugally unbound. Therefore the centrifugal force at the surface of the star should not exceed the gravitational attraction. i.e. \( \omega_0 \simeq 0.6 \). This condition yields

\[
R_2 \omega_2 \geq (m_0 \omega_2)^{2/3} (m_2(m_1 + m_2))^{1/3}.
\]

(8a)

For \( \omega_0 = 1.4 \) and \( 2 \omega_0 \) and \( 4 \omega_0 \) this yields \( R_2 \omega_2 \leq 0.8 \) and \( \leq 0.63 \) respectively.

Secondly, the compact object which travels in a low orbit over the surface of the normal star should not disrupt the envelope of the latter. We can estimate the minimum height of the orbit of the compact object by using an impulse-approximation. The momentum \( \dot{\lambda} \) transferred to a unit mass at the stellar surface, can be estimated from

\[
\dot{\lambda} \simeq F h / v_0.
\]

(8b)
Fig. 1. Upper limits to the orbital period in the non-synchronous case, as a function of the mass $m_2$ of the early-type star for compact companions of 1.5 $\mathcal{M}_\odot$ and 8.0 $\mathcal{M}_\odot$, respectively. Parameters is $\omega_1, \omega_0$ (the ratio of the rotational and orbital angular velocities). For $m_1 = 8.0 \mathcal{M}_\odot$ and $\omega_1, \omega_0 = 1.4$, the parts of the curve for $m_2 \leq 8.0 \mathcal{M}_\odot$ are uncertain (see text).

and 8 $\mathcal{M}_\odot$, respectively. It appears that for $m_1 = 1.5 \mathcal{M}_\odot$ and $\omega_1, \omega_0 \geq 1.2$, as well as for $m_1 = 8.0 \mathcal{M}_\odot$ and $\omega_1, \omega_0 \geq 1.7$, the upper limit due to the centrifugal condition is below that due to the impulse condition for any $m_2 \geq 6.0 \mathcal{M}_\odot$, implying that the centrifugal condition should be used in these cases. Using this limit one can, with Eq. (6) and assuming $P_{\omega} = 164^\circ$, again calculate the upper limits to the orbital period required for producing the observed precession. Figure 1 depicts the thus obtained upper limits for the above mentioned sets of parameters, and $k/k_0 = 3$. For $m_1 = 8.0 \mathcal{M}_\odot$ and $\omega_1, \omega_0 = 1.2$ and 1.4, the curves for $m_2 \leq 30 \mathcal{M}_\odot$ and $< 24 \mathcal{M}_\odot$, respectively, are determined by the impulse condition and have a different shape, as depicted in Fig. 1.

In fact, for $m_1 = 8.0 \mathcal{M}_\odot$ and $m_2 \leq 10 \mathcal{M}_\odot$, it is no longer clear what limit should be taken. Because, when $m_2$ and $m_1$ are approximately equal, the tidal forces due to the 8 $\mathcal{M}_\odot$ compact star will be felt everywhere around the surface of the normal star and hence, the impulse approximation becomes too crude. One would expect in this case the upper limit to the radius to have a value somewhere between the centrifugal limit and the Roche-lobe radius. Adopting for the mass range $m_1 \leq 10 \mathcal{M}_\odot$, a maximum value of $R_c$ halfway between these two limits one obtains orbital periods in the range 9 to 14 d.

In Table 1 the upper limits resulting from the above analysis are summarized for the cases $m_2 = 20 \mathcal{M}_\odot$ and 6.0 $\mathcal{M}_\odot$ with $\omega_1, \omega_0 = 1.4$ and 2.0 (for the case $m_2 = 6.0 \mathcal{M}_\odot$, $m_1 = 8.0 \mathcal{M}_\odot$, $\omega_1, \omega_0 = 1.4$, the upper limit to $R_c$ was taken halfway between $R_{\text{Roche}}$ and the centrifugal limit). The table shows that for non-synchronous rotation the orbital periods allowed for driven precession in an early-type binary model extend to 16 d for a black hole companion and to over 9 d for a neutron star companion. Taking into account the $(1-e)^{-3/2}$ factor and the various approximations made, the actual upper limits may easily be 50% higher.

3. Comparison with the Observations

3.1. Binary Periods Allowed by the Spectroscopic and Photometric Observations

Crampton et al.'s (1980) observations suggest a 13.1 d periodicity in the radial velocities of the "stationary" hydrogen emission lines in SS 433. If this is the true orbital period and the 164-d period is due to tidally driven precession ("slaved disk") then, according to Table 1, regardless of whether the compact star is a neutron star or a black hole, the only possible early-type configuration is one in which the companion is rotating (highly) non-synchronously. In the case of a neutron star, the early-type star should be a Wolf-Rayet star, in case of a black hole, also Of-stars are allowed.

On the other hand, the table shows that if the companion is close to co-rotation, only binary period of the order of one day or less can explain the 164-d precession [assuming the precession to be tidally driven; the same is true for most other precession mechanisms, cf. Katz (1980) and Davidson and McCray (1979)]. We would like to point out here that orbital periods near one day have, in fact, not been ruled out by Crampton et al.'s spectroscopic observations and might still be allowed by the extensive photometric observations by Kemp et al. (1979). The argumentation is as follows. If the true orbital period is close to one day, i.e. either 13/12 of 13/14 d (26 or 22 h, respectively), observations spaced by multiples of one day will give the impression of a 13-d periodicity. Crampton et al. did not favour this possibility but could not rule it out convincingly, as Fig 2 demonstrates. In this figure the observations by these authors...
have been plotted in the three best-fit periods, viz. 13.1, 0.923 and 1.081. The mean deviations in the least-squares fit for these three periods are 25 km s\(^{-1}\), 37 km s\(^{-1}\), and 27 km s\(^{-1}\) respectively, i.e. the 1.081 period is only slightly less significant than the 13.1-d period, and the 0.923-d period still has a reasonable significance (as the total velocity range is \(\sim 150\) km s\(^{-1}\)). Gladyshev et al. (1979) and Kemp et al. (1979) established a photometric period of roughly 6.5 d, i.e. about half the radial-velocity period. This situation strongly resembles that of the massive X-ray binaries, where the photometric variations show a double-wave behaviour, due to the tidal deformation of the (nearly) Roche-lobe filling component.

If the true orbital period is 22 (26) h, one would, for a tidally deformed star, expect an 11 (13) h photometric periodicity (i.e. near one half day alias of Kemp et al.'s 6.5-d periodicity). While Kemp et al. were able to strongly exclude the one-day aliases of the 6.5-d period, they could not make a clear statement about half-

day aliases. The reason is that their photometric data were obtained at two observatories which are separated in longitude by more than 10 h (one in Oregon and one in Israel), i.e. close to the 11h double wave periodicity expected in the case of a 22h orbital period.

For this reason especially a 22h orbital period can probably not yet be ruled out as it would fit the existing spectroscopic and photometric observations. (Because of the large random variations in the photometric data it is quite likely that also a 26h period is not yet ruled out.)

One might argue that a photometric period of 11h (13h) would be simply detectable during a one night observing run. However, the large intrinsic scatter in the form of rapid photometric changes by several tenths of a magnitude within a few hours (Kemp et al., 1979) renders such a test quite difficult and will require observations during a sufficiently long time interval to disentangle periodic effects from non-periodic ones. What would be most needed are data from two observatories separated in longitude by about 6 h.

3.2. Constraints Derived from the Observed Radial Velocity Amplitude

Since both a 13h and a 22h (26h) orbital period might fit the observations we now examine for both cases the mass of the optical star resulting from the radial velocity amplitude of 73 km s\(^{-1}\) measured by Crampton et al. (1979).

(i) \(P = 13.1\) d. The resulting mass function in this case is

\[
f(\mathcal{H}) = m_1 \sin^3 \theta (1 + m_2/m_1)^2 = 0.53 . \mathcal{H}_e .
\]

Assuming \(m_1 = 1.5 \mathcal{H}_e\) (neutron star) one finds that \(m_2\) should fulfill the inequality

\[
m_2 \leq 1.033 \mathcal{H}_e .
\]

Alternatively, if the compact star is a black hole with a mass \(m_1 = 8. \mathcal{H}_e\), the condition becomes

\[
m_2 \leq 23.2 \mathcal{H}_e .
\]

(ii) \(P = 22\)h (26h) results in

\[
f(\mathcal{H}) = 0.037 (0.044) . \mathcal{H}_e\]

which with \(m_1 = 1.5 \mathcal{H}_e\) similarly yields the condition

\[
m_2 \leq 8.0 \mathcal{H}_e (7.3) . \mathcal{H}_e .
\]

1. Recently Dr. Kemp informed us that he can probably rule out periods near 11h or 13h, such that binary periods near 1 day would be excluded. Furthermore, Margon et al. have found evidence for a 13-d modulation in the flux of the stationary emission lines, thus strengthening the likelihood of a period near 13 d.

### Table 2. Summary of the constraints on early-type binary models with tidally driven precession, derived from the 164-d (precession) period and the 73 km s\(^{-1}\) radial velocity amplitude. Admitted early-type stars are indicated as WR (\(m_2 < 10. \mathcal{H}_e\)) or Of stars (\(m_2 > 10. \mathcal{H}_e\)).

<table>
<thead>
<tr>
<th>Period:</th>
<th>Compact object:</th>
<th>Constraints:</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P = 1) d</td>
<td>Neutron star: (m_1 = 1.5 \mathcal{H}_e)</td>
<td>Good fit with synchronous rotation WR or Of</td>
</tr>
<tr>
<td>&amp; Black hole: (m_1 = 8. \mathcal{H}_e)</td>
<td>Good fit with synchronous rotation WR or Of</td>
<td></td>
</tr>
<tr>
<td>(P = 13) d</td>
<td>Neutron star: (m_1 = 1.5 \mathcal{H}_e)</td>
<td>Fit with (highly) non-synchronous rotation WR</td>
</tr>
<tr>
<td>&amp; Black hole: (m_1 = 8. \mathcal{H}_e)</td>
<td>Fit with (highly) non-synchronous rotation WR or Of</td>
<td></td>
</tr>
</tbody>
</table>

* With an inclination \(i \approx 80^\circ ; m_2 \approx 100. \mathcal{H}_e\). A lower-mass black hole, e.g. \(m_1 = 4. \mathcal{H}_e\), would fit with an Of star.

b Fit possible, only if radial velocity amplitude has an alternative explanation (see text).
3.3. Constraints Set by the Precession and Mass Function Combined

The constraints (10a, b) and (11a, b) set by the mass function, together with the constraints from Table 1 and Fig. 1, set by the precession, yield the following conclusions (summarized in Table 2) for the case of a 13.1 d period, where the deviation ranges from 4% (for a black hole) to 7% (for a neutron star).

(i) For a binary period of about 1 d both the precession (if tidally driven) and the mass function can be obtained with a synchronously rotating (though misaligned) early-type companion, which, in the case that the compact star is a neutron star, should be a Wolf-Rayet star ($m_* \leq 10^3 M_\odot$), according to the mass function).

(ii) If the orbital period is 13.1 d, the precession (if tidally driven) can only be explained if the rotation of the early-type companion is highly non-synchronous; furthermore, if a compact star is a neutron star, the mass function cannot be fitted with an early-type star.

The latter fact does, however, not necessarily rule out a neutron star in a 13.1 d binary, neither does it rule out an early-type companion. Because, it is not clear that the observed radial velocity amplitude of the emission lines necessarily represents the orbital motion of the early-type star; notably, in some X-ray binaries e.g. Cygnus X-1 and LMC X-4) the emission-line radial velocities represent the orbital motion of the compact star, which has a very large radial velocity amplitude. If the velocity amplitude of the emission lines in SS 433 is associated with a disturbance in the wind of the early-type star, generated by the orbital motion of the compact star through this wind, or to a cloud of gas around the compact star, the maximum value possible for the amplitude would be a few hundred km s$^{-1}$, hence, an amplitude of $\sim 13$ km s$^{-1}$ could certainly be generated.

3.4. Further Constraints Set by the Stationary Spectrum and Absolute Luminosity

Adopting a distance $\geq 3.7$ kpc and an interstellar extinction $A_V \approx 6$ $^m$ to 8$^m$ (Giles et al., 1979; Murdin et al., 1980) the absolute magnitude of SS 433 at least $M_V \approx -4^m$ to $-6^m$. The presence of He I 4686 and C III N 4640 in emission indicates $T_e \gtrsim 3 \times 10^4 K$, which implies B.C. $\geq 3^\circ$, yielding $M_V \approx -7^m$ to $-9^m$. We now consider how these parameters fit with the above derived possible system configurations.

a) $P = 13.1$ d.

In this case, assuming the compact star to be a neutron star, the companion should be a non-synchronously rotating WR star with $(\omega_1 \approx 1.4 \omega_0$ and $m_* \approx 8 \cdot 10^3 M_\odot$) a radius of $\sim 35 R_\odot$. Such radii are similar to those of the latest types WR stars, i.e. the WN7 to WN9 stars, which have $T_e \approx 25,000$ to $30,000 K$, $M_* \approx 7^m$ to $9^m$ and $R \approx 35 R_\odot$ (Conti, 1979; Leep, 1979). Since WN7-9 stars are, at the same time the only WR stars that clearly show hydrogen emission lines (Conti, 1979), this WR configuration would fit excellently with the $M_*$ and the characteristics of the stationary spectrum of SS 433. Although it would not fit the mass function, this would not necessarily pose a problem (cf. Sect. 3.2).

If the compact star is a black hole, a 13.1 d period will also allow non-synchronously rotating Companion stars, which also fit the observed spectrum and $M_*$ (cf. Paper I), as well as the mass function.

b) $P > 1$ d.

Here a neutron star with a $20 \cdot 10^3 M_\odot$ Companion would require a stellar radius $\leq 7 R_\odot$; with a $6 \cdot 10^3 M_\odot$ WR star one should have $R \leq 5 R_\odot$. The latter radii are characteristic for early-type WR stars which, however, do not show hydrogen emission (cf. Conti, 1979). So, in this case only Of companions would remain and indeed $7 R_\odot$ is just about the lower limit of the observed radii of such stars, as derived from their effective temperatures and luminosities (cf. Conti, 1969).

If the compact star is a black hole the conclusions are similar.

3.5. Summary of the Possible System Configurations

Combining the results from Sects. 3.2 and 3.3 and keeping in mind that alternative explanations for the mass function are possible, we observe that:

a) In the case of a neutron star only two viable alternatives remain, i.e. (i) a 13.1 d orbit with a non-synchronously rotating WN7-9 Companion with, for $\omega_1 \approx 1.4 \omega_0$, a mass $m_* \approx 10^3 M_\odot$ (cf. Fig. 1). The radial velocity amplitude is in this case not due to the orbital motion of the WN star itself but should be explained by other causes; (ii) a $\approx 1$ d orbit with a synchronously rotating WR Companion. If the radial velocity amplitude is not due to orbital motion of the early-type star, also Of stars are allowed.

b) If the companion is a black hole, the conclusions are the same with the addition that in the 13.1 case also Of companions (mass range $10 \sim 30 \cdot 10^3 M_\odot$) are allowed and the observed radial velocity amplitude may be explained as due to the orbital motion of the early-type star itself.

References

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