for the major observational features of the ε Aur system. Because of the intrinsically great interest in the possible discovery of a collapsar, it is recommended that much more observational attention be paid to ε Aur, particularly in the infrared. Improved orbit determinations are also very desirable, and continued photometric coverage during eclipses.

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Collapsars, Infrared Disks and Invisible Secondaries of Massive Binary Systems

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The supergiant primary of the eclipsing binary system ε Aur is probably a star of high mass burning helium in its core. Cameron's suggestion that the invisible secondary is a massive collapsar surrounded by a cool disk of solid particles is thus given further support. A similar object with a disk may be in orbit around the supergiant 89 Her, which has a large infrared excess of unknown origin. The disk could be formed during the initial stage of collapse of the secondary.

INTERPRETATION of the binary system ε Aur has always been hampered by observational difficulties. The system consists of a supergiant primary, with a spectrum which is most commonly classified[1] in the range A8 Ia to F2 Ia, and a peculiar invisible secondary. The orbital period is 27 yr, and the primary undergoes eclipses in which the light from the eclipsed star is never completely extinguished. The mass function of the system is 3.1 $M_\odot$.

Kopal (in unpublished work) has argued convincingly against earlier theories of ε Aur and has interpreted the secondary as a large semitransparent disk composed of solid particles, in a prestellar stage of evolution. Thus the primary would of necessity be a massive star in its pre-main-sequence phase of evolution, crossing the H–R diagram as a yellow supergiant. Cameron, in the preceding article, has criticized this interpretation on several counts, although he accepts the existence of the disk of particles. In his view, the primary is an evolved star of high mass, and the secondary, originally the more massive star, has completed its evolution and is at present a collapsar of extremely small radius; the disk (of small mass in Cameron's theory) has been accreted from the interstellar medium. Previously Trimble and Thorne[2], in their unsuccessful search among known binaries for a possible collapsed object, mentioned the companion of ε Aur as a possible candidate but rejected it on rather superficial grounds.

It has been assumed that the bright luminosity classification of the primary star implies a high mass. That this is not necessarily so can be demonstrated simply from the parameters which specify a stellar atmosphere: namely its chemical composition, effective temperature and surface gravity. Certain models of stars with initially low to moderate mass (refs. 3 and 4 and unpublished work of W. Deinzer) can, in very distended states of advanced evolution after mass loss, attain the specific characteristics of a yellow Ia supergiant. Furthermore, not only is their lifetime in this state comparable with the lifetime of a massive supergiant with the same spectral type, but in general, the birth rate of low-mass stars in space is very much greater than that of massive stars. If ε Aur were an evolved system containing two low-mass stars, then the disk around the secondary star could conceivably contain a main-sequence star, or a white dwarf, or even a neutron star. Because the mass of the secondary system is high (3.6 $M_\odot$) even in the limit of a very small mass of the primary, the disk would have to be fairly massive if a collapsar or main-sequence star is not embedded inside. Clearly it is important to establish the mass and evolutionary stage of the primary of ε Aur in order to interpret the secondary, and this is the object of this article.

The position of ε Aur on the sky is not far from that of the association of stars known as Aur OB1. The IAU[5] boundaries of the association are: $l^{II} = 168°$ to $178°$ and $b^{II} = -7°$ to $+4°$; ε Aur is located at $l^{II} = 163°$ and $b^{II} = +1.2°$. Several possible members of Aur OB1 have been listed by Morgan, Whitford, and Code[6] and by Humphreys[7]. To construct an accurate H–R diagram for the association, the stars listed by these authors and additional stars from Hiltner's[8] general list of OB stars lying within the formal projected boundaries of the association have been examined for membership on the basis of their radial velocities and apparent magnitudes. Radial velocities were taken from the catalogues of Wilson[9] and of Petrie and Pearce[10]; V and B magnitudes from Blanco, Demers,

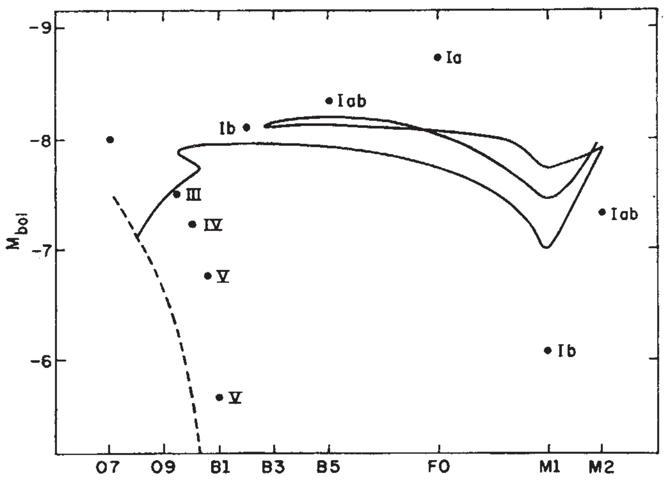

Fig. 1 Bolometric H–R diagram for probable members of the association Aur OB1. Luminosity classes of the stars are indicated (- - -), unevolved main sequence; (——), evolutionary track of a star of 20 $M_{\odot}$. HD 35601 (M1 Ib) may belong to an older population group in Aur OB1, containing also HD 35600 (B9 Ib); this is further suggested by the long evolutionary deviation of the main sequence.

Douglass, and Fitzgerald[11]; intrinsic B–V colours, bolometric corrections, and effective temperatures from Morton and Adams[12] (for OB stars), Johnson[13] (for A to K supergiants), and Lee[14] (for M supergiants). A ratio of total-to-selective extinction given by $A_V/E_{B-V}=3$ has been adopted. The IAU distance to Aur OB1 is 1.34 kpc, which agrees very well with the value derived here from the unreddened apparent magnitudes of the main-sequence stars and Blaauw's[15] calibration of their absolute magnitudes.

Table 1 Probable Members of the Association AUR OBI

Star	Sp	v_{rad} (km/s)	E_{B-V}	M_{bol}
HD 31327	B2 Ib	−5	0.59	−8.1
HD 34656	O7f	0	0.34	−8.0
HD 34921	BO IV: pe	−9	0.44	−7.2
HD 35345	B1 Vpe	+4	0.47	−5.7
HD 35601	M1 Ib	−1.2	0.50	−6.1
HD 35653	B0.5 V	+3	0.40	−6.8
HD 36371	B5 Iab	−0.2	0.42	−8.3
HD 36483	09.5 III	+6	0.73	−7.5
HD 37536	M2 Iab	+4.8	0.41	−7.3
ε Aur	F0 Ia	−2.5	0.35	−8.7

Table 1 lists nine stars which are considered to be association members. Their mean radial velocity is 0 ± 5 km/s, and their mean colour excess is 0.48 ± 0.11 mag., to be compared with −2.5 km/s and 0.35 mag. for ε Aur. The mean annual proper motion of the nine stars, the motions of which are listed in the Smithsonian catalogue[16], is $<\mu_\alpha> = +0.003''\pm0.006''$, $<\mu_\delta> = 0.000''\pm0.004''$, where the standard error of the mean motion is here given. With $\mu_\alpha= +0.001''\pm0.001''$, $\mu_\delta= -0.004''\pm0.001''$, ε Aur could very well be an association member. How much of the measured proper motion is due to orbital motion is not known. Finally, by adopting the distance modulus determined for Aur OB1, an absolute visual magnitude of −8.7 is found for ε Aur. This is not incompatible with the value of -8.2 ± 0.6 derived from Strand's[17] combined orbital and astrometric parallax; −7.5 quoted by Morris[18] as having been estimated from the strength of interstellar lines; and −8.5 listed by Blaauw[15] as the average absolute magnitude for an F0 Ia supergiant.

Comparison of polarization measurements of ε Aur by Hall[19] with those of OB stars in the general region surrounding ε Aur[8] gives no further information about the distance of the star. Nor is the spatial arrangement of H I in this general direction usefully determined by 21 cm observations[20], because of the lack of distance resolution close to the direction of the galactic anticentre. Although the complex of H II regions in the vicinity[21] seems to be physically associated with Aur OB1, the complex does not extend as far as ε Aur, so that the star is not as clearly affiliated with Aur OB1 as, for example, α Ori is with Ori OB1 (ref. 22). A survey of the list of B stars in Hiltner's[8] catalogue reveals that no possibility exists of a hitherto unrecognized association around ε Aur itself. Certainly the star does not belong to the nearby cluster NGC 1664 ($l^{II}=162°$, $b^{II}=-0.5°$, r=0.5 kpc)[23] because the mean colour excess of the cluster is only 0.16 mag., ε Aur lies about 12 cluster radii from the cluster centre, the earliest spectral type of the certain main-sequence members is A0, and the absolute magnitude of ε Aur would be only −6.5 if it were a member. It is equally unlikely that ε Aur is a runaway star from the much more distant association Aur OB2 ($l^{II}=173°$, $b^{II}=0°$, r=3.6 kpc). First, the most certain members of Aur OB2 in the IAU list[5], the O stars, have a very large mean colour excess, 0.60 mag. Second, if ε Aur originated at the centre of the association, it would be expected to have a space velocity of at least 200 km/s, and thus an annual proper motion of $\mu=0.012''$. Third, its absolute magnitude would be unreasonably bright, −10.8 mag., which would require it to have the spectroscopic characteristics of a super-super-giant[24], whereas the spectrum seems to resemble basically that of a normal yellow Ia supergiant, particularly in the width of its lines[25]. It is safe to conclude that ε Aur lies at approximately the distance of Aur OB1 and is physically associated with it.

The H–R diagram of the association members is shown in Fig. 1, with the unevolved main sequence[26] plotted as a dashed line and the theoretical evolutionary track[27] for a star of 20 $M_{\odot}$ as a solid line; the uncertain effective temperature of the cool portion of the theoretical track has been adjusted to agree with the observational data for M supergiants.

Apparently, the mass of observed stars that have evolved off the main sequence of Aur OB1 is close to 20 $M_{\odot}$. Epsilon Aurigae appears brighter (younger) than the other supergiants if it is an association member. This can be interpreted in several ways, each of which will now be considered in turn.

First, the interstellar extinction for ε Aur may not be as large as has been supposed. The intrinsic B–V colour for an F0 supergiant is given by Johnson[13] as +0.19, but two of the values given elsewhere[28,29] are +0.24 and $+0.07\pm0.07$. To bring the luminosity of ε Aur down to the level of the blue supergiants in Aur OB1 requires an intrinsic B–V colour of about +0.34, corresponding, in Johnson's[13] calibration, to a spectral type of F4. Such a value of intrinsic colour or even a spectral type of F4 is not impossible for ε Aur, because of the paucity of suitable standards for Ia supergiants.

Second, because Aur OB1 is a very young association, it is possible that star formation is still going on. The age of the association based on the location of the main-sequence turnup on the H–R diagram is about 7.5×10^6 yr (assuming an initial hydrogen content of 70%), and it is well known that star formation in some young stellar groups can extend over as much as 10^7 yr[30]. As if in support of this idea, there is the possible presence of an O7f star in Aur OB1 (Fig. 1). Now ε Aur lies at least 230 pc from the centre of Aur OB1, and, if it was formed inside the association, it must surely be old compared with the 10^3–10^4 yr which represent the pre-main-sequence age of a massive yellow supergiant[31]; otherwise ε Aur would have an enormous space velocity. Although massive stars may not always form in associations, the available evidence to the contrary is scarce and not very conclusive[32]. It is thus reasonable to conclude that ε Aur is in a post-main-sequence phase of evolution.

If ε Aur has travelled from the centre of Aur OB1 out to a distance of 230 pc during a lifetime of 6.5×10^6 yr (appropriate for a primary mass of 25 $M_{\odot}$), then its local space velocity would be about 35 km/s, which is also its orbital velocity for this mass. A velocity of 35 km/s is equivalent to a (maximum) annual proper motion of $\mu = 0.0055''$ at a distance of 1.34 kpc. This is within the error of the (undetected) relative proper motion between ε Aur and the centre of Aur OB1, and so one cannot reject the idea that ε Aur was born inside the association.

With this conclusion, one can proceed to discuss the evolution of massive stars in connexion with ε Aur. Theoretical evolutionary tracks for stars of high mass cross the H–R diagram at roughly constant luminosity three times while the core burns helium. (Some models give only one crossing—occurring at the end of core helium burning—but the distinction is unimportant here.) Because a fossil H II region[33] is not observed around ε Aur, it seems likely, though not obligatory, that the primary star is in the second or third post-main-sequence crossing. Mass loss from the stellar surface has virtually no effect on the luminosity or lifetime of the star once the helium core is formed, so the observed luminosity of the primary can be correlated reliably with its original main-sequence mass[34]. This mass is about 25 $M_\odot$, as I have assumed. A lower limit on the mass is provided by the mass of the original helium core of 7 $M_\odot$, for an absence of the hydrogen envelope would prevent the radius expansion necessary to account for the distended characteristic of a yellow supergiant[35]. Because the percentage of mass actually lost is likely to be slight in the case of a star of such high mass[36], a probable value of 25 $M_\odot$ has been adopted for the primary of ε Aur. By using the orbital mass function[40] of 3.1 $M_\odot$ and an approximate orbital inclination[17] of 72°, the mass of the secondary comes out to be 19 $M_\odot$. (In the highly unlikely event of a primary mass of 7 $M_\odot$, the secondary's mass is 10 $M_\odot$—still a very large value.)

In the preceding article Cameron has already assumed that the primary has a high mass and is in a post-main-sequence phase of evolution. Therefore, I accept his necessary conclusion that the secondary must have already completed its evolution and so have had originally a larger mass. The original mass probably did not exceed 60 $M_\odot$[38], which then sets an upper limit on how much mass could have been lost through stellar winds, mass exchange and events attending formation of the remnant. By the same token, the lifetime of the secondary in its present state could not have exceeded about 3×10^6 yr. Cameron suggests that the high mass of the secondary is consistent only with the assumption of a collapsar.

It is possible, though unlikely, that a relic of the event which formed the collapsar is the extended radio[39] and optical[40] nebula HB 9 ($l^{\text{II}} = 161°$, $b^{\text{II}} = +2.8°$). The angular diameter of the nebula is about 2.3°, and its distance is variously estimated as between 1.1 and 1.9 kpc[41–43]. The object seems to be a typical type II supernova remnant[41,44] and so, on this basis alone, is probably derived from a massive star. But there is no known pulsar[45] or discrete X-ray source[46] in the general area. There are, however, reasons for rejecting the association of HB 9 with ε Aur. HB 9 lies about 2° north of ε Aur and on the side of ε Aur away from Aur OB1. Furthermore, there is no compelling theoretical reason for a special relic of this nature attending the uninterrupted collapse of a massive object.

If, instead, the bulk of the collapsing star at the initial period of collapse had shrunk to a very small radius while conserving the angular momentum of its outer (or circumstellar) portions by forming a flattened disk of small mass, the disk would be expected to possess the chemical composition and radial extent of the original star just before the collapse. Recent models[47] indicate that this pre-collapse object would be a cool, highly luminous star with an enveloped enriched in the CNO elements and extending to a radius of, very approximately, 2000 $R_\odot$. The disk in ε Aur has a radius lying in the range 1000–4000 $R_\odot$ (ref. 48, Cameron's article and Kopal's unpublished work) and, quite possibly, a chemical composition of largely graphite if the analogy with 89 Her is adopted as below. It is probably not unreasonable to suppose that most of the gaseous component has been incorporated into grains or else lost owing to the low gravity. The disk must be moderately thick, or tilted to the orbital plane, in order to produce the observed eclipses. It is understandably very dark, having had possibly millions of years to cool off.

The time scale of collapse of the massive central star to a radius close to the Schwarzschild radius is only a few years. During this time the star radiates away most of its energy in the form of neutrinos and loses its excess rotational angular momentum by the emission of gravitational waves[60]. Theoretical models indicate that no matter is blown off the surface, but that the equivalent mass of emitted neutrinos can be very large[61]. Clearly the surrounding disk of solid particles will not be disrupted, because of the virtually noninteracting nature of the star's dominant forms of emission. Subsequent contraction of the central star is very slow (as seen by an external observer), and the star becomes very dim and red, pinching itself off gradually from the rest of the universe[60].

A third possible interpretation of the luminosity of ε Aur is that the evolving system previously suffered mass exchange, suddenly increasing the mass of the primary to 25 $M_\odot$ at the expense of the mass of the secondary. This would account for the delayed formation of a star of 25 $M_\odot$ in an association where normal evolution is now taking stars of 20 $M_\odot$ off the main sequence. It would also account for the paradoxically smaller mass of the more highly evolved secondary. Nevertheless, because the large number of calculated mass-exchange models seem to indicate that the evolving star is always stripped practically down to its core, some mass must have been lost from the system of ε Aur as a whole during the exchange process in order to leave a core of 19 $M_\odot$ in a system which has a present total mass of 44 $M_\odot$. The large observed separation of 6900 $R_\odot$ between the components should not necessarily be construed as evidence against any previous mass exchange, because a massive star during the M-supergiant phase can attain an almost comparable radius of 2000 $R_\odot$, and an exchange of mass at that time might result in the observed separation of the components.

A fourth possible interpretation of the luminosity of ε Aur is that the star is actually in the foreground of Aur OB1. Since ε Aur lies on the north-west edge of Aur OB1, there is no reason to reject its being also somewhat in front. The total extent of the association perpendicular to the line of sight is about 230 pc, and the projected distance of ε Aur from the centre is also about 230 pc. A true distance from the centre equal to approximately twice the transverse extent of the association would be required to bring the luminosity of ε Aur down to a value compatible with that of the blue supergiants in Aur OB1. This rather difficult requirement (if ε Aur is an association member) means that the original mass of the primary of ε Aur could not have been less than about 20 $M_\odot$.

A further check on the mass of the primary is provided by the average frequency of its irregular fluctuations in light, colour, and radial velocity[37], the occurrence of which is not unusual for bright yellow supergiants[49]. If these fluctuations are due to radial pulsation in the fundamental mode (with much interference), then

$$\frac{M}{M_\odot} = \left(\frac{L}{L_\odot}\right)^{3/2} \left(\frac{T_e}{T_{e\odot}}\right)^{-6} \left(\frac{Q}{P}\right)^2$$

which simply combines the Stefan-Boltzmann law for the surface flux with the definition of the pulsational Q value. Theoretical models[38,50,51] of supergiants with radiative envelopes are characterized by $Q = 0.04$ day. If one adopts $P = 100$ days, $T_e = 7{,}000$ K[57], and $M_{\text{bol}} = -8.7$, the mass of the primary of ε Aur turns out to be 6 $M_\odot$. To appear at the present time as a Ia supergiant, the star must be overluminous for its mass (low surface gravity) and therefore have lost mass at an earlier period, being originally of 10–20 $M_\odot$ (hence still consistent with membership in Aur OB1).

It is not obligatory to conclude, however, that extensive mass loss from the primary has occurred. Rather, to achieve a present mass of 25 $M_\odot$ for the primary from the expression I have just given, one might adopt $Q=0.08$ day or $T_e=5,500$ K (both of which are probably unrealistic) or $P=50$ days, which is more realistic in view of the uncertainty of the "period" of the observed fluctuations. Furthermore, the fluctuations may not be due to the fundamental mode of radial pulsation at all. Thus one finds no real contradiction of the preceding result that the primary of ε Aur is a massive star of (at least originally) 20–25 $M_{\odot}$.

Eventually, the faint absorption lines due to the dilute gas surrounding the secondary and appearing in the visual part of the spectrum during eclipse[50] may be detected outside eclipse as well, leading to a second radial-velocity curve and a direct determination of the masses. Infrared lines might also be sought, although the secondary is known[53] not to emit infrared radiation in any appreciable amount at wavelengths shorter than 9.2 μm.

In this connexion, it may be highly significant that Gillett, Hyland, and Stein[54] found an unexpected large flux of constant, continuous infrared radiation coming from the otherwise normal F2 Ia supergiant 89 Her. They have suggested that a shell of solid particles at a temperature of 200–600 K surrounds the star, which does not seem to share this property with other typical yellow supergiants. An alternative explanation, however, might be that a cool disk of solid particles is surrounding an invisible secondary in a binary system containing 89 Her as the primary; the orbital period is probably rather long, for 89 Her is not known to be a binary. Although radial-velocity[55] and light[56] variations in this star have been observed (with a characteristic period of about 70 days), they are clearly not due to orbital effects. The infrared disk of solid particles is assumed here to be associated with an invisible secondary star, rather than to have been accreted from the interstellar medium by an assumed single F star, because 89 Her lies at high galactic latitude where the density of interstellar material is relatively low, and because other yellow Ia supergiants at low galactic latitudes do not show an unexpected infrared excess. The disk in 89 Her must be more massive, or more recently formed, than that in ε Aur because of its larger (that is, detected) infrared flux. The model proposed here removes various difficulties encountered by the assumption of a spherical shell around 89 Her: namely, the apparent invisibility of the shell at optical wavelengths, the difficulty of forming solid particles in a relatively hot atmosphere, the lack of similar circumstellar shells around other yellow Ia supergiants that are known to be losing mass (including ε Aur[48]), and the probable graphite composition of the radiating particles[57]. Like ε Aur, 89 Her seems to have moved considerably from its place of origin[60], has no listed H II region surrounding it[21], and is probably an evolved star. No trace of nebulosity around it is seen on the Palomar Sky Survey plates. Furthermore, there is no listed supernova remnant[41,43], pulsar[45] or discrete X-ray source[46] anywhere near the star, although three unidentified radio sources in the 4C catalogue[58] have positions nearby. It is therefore quite possible that 89 Her belongs to a new class of stars the prototype of which is ε Aur.

In conclusion, there seems to be fairly good reason to believe that the primary of ε Aur is a star of high mass which has evolved past the main sequence, being at present in the main phase, or in a peripheral phase, of core helium burning. If this is correct, the massive secondary must be an even more evolved object, and, as Cameron has pointed out, it can really only be a collapsar. A similar object may be in orbit around 89 Her and possibly around other stars that have an unexpected infrared excess. (Perhaps some of the presently unidentified[59] infrared or OH sources with small angular diameter are also disks containing collapsars, since collapsars are obviously not restricted to binary systems.) The curious infrared excess emitted by these composite objects arises not from the collapsar itself, but rather from the spiralling stream of particles around it.

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