## Contact binaries The astrostrophic balance

Wed, 13 Jan 2016 | Angular Velocity

In Sections 4.6 and 8.2-8.4 we have considered detached close binaries, in which the tidal distortions are relatively small and where components display physical characteristics that are similar to those of single stars. When the two components are separated by a few radii only, these tidal distortions may become, however, quite large. This is well illustrated by eclipsing binaries that exhibit sinusoidal-type light curves, and for which the first-order scheme of approximation adopted in the above sections becomes utterly inadequate. In what follows I shall thus consider the Roche model, in which practically all the mass of each component is concentrated in a central point surrounded by a tenuous envelope of vanishingly small density. * The importance of this model stems from the fact that it provides a good approximation for binary components that are in physical contact and share a common envelope.

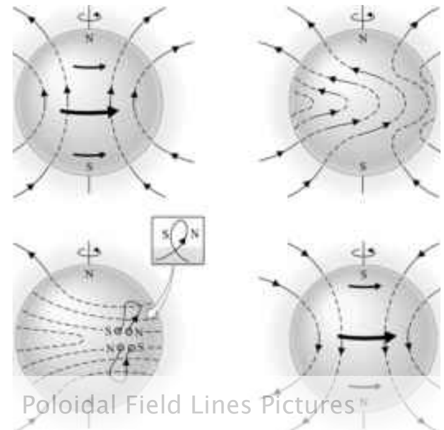
Let Mu and Mju denote the masses of the two components, and let D be their mutual separation. We choose a rotating frame of reference with the origin at the center of gravity of the mass Mu. The x axis points toward the center of gravity of the mass Mju, and the z axis is perpendicular to the orbital plane. The effective gravity at any point P can be described as the gradient of a potential ^, where

in which ru and rju are the distances from P to the centers of gravity of the two masses. Let us further assume that the rotational angular velocity occurring in Eq. (8.60) is equal to the Keplerian orbital angular velocity. We thus let

If we adopt D as the unit of length and GMu / D as the unit of potential, we can then write (except for an additive constant)

V = - + q( — - x) + 1 (1 + q)(x2 + y2), rj \rn J 2

* The geometry of the equipotentials that surround a rotating gravitational dipole was originally investigated by the French mathematician Edouard Roche (1820-1883) in 1873. For a detailed historical account the reader should consult Kopal's (1989) book.



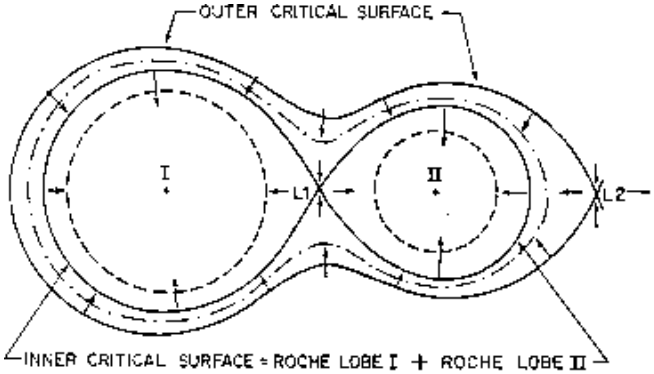



Fig. 8.5. The inner and outer critical surfaces of the binary Roche model plotted in the equatorial plane. The arrows indicate the direction of the effective gravity. For a detached system, the two stellar surfaces (dashed curves) both lie beneath the inner critical surface; for a contact binary, the common stellar surface (dash-dotted curve) lies between the inner and outer critical surfaces. Source: Shu, F. H., Lubow, S. H., and Anderson, L., Astrophys. J.209, 536, 1976.

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Figure 8.5 represents a section of the equipotentials ^ = constant cut by the orbital plane z = 0. Quite generally, level surfaces corresponding to high values of ^ form separate lobes enclosing each one of the two centers of gravity and differ little from spheres. With diminishing values of ^, the two lobes become increasingly elongated in the direction of their common center of gravity until, for a certain critical value ^ = ^in characteristic of each mass ratio, both lobes will come into contact to form a dumbbelllike configuration. It will henceforth be called the inner critical surface, and its two lobes will be called the Roche lobes. Note that the Roche lobes unite at a point where the effective gravity vanishes (i.e., at the Lagrangian point L j). For even smaller values of ^, the connecting part of the dumbbell will open up so that single level surfaces enclose both bodies, thus providing us with a convenient representation of a contact binary. Below a critical value ^ = ^out (<^in) characteristic of each mass ratio, however, gravitational confinement of a binary against the expansive tendency of its internal pressure is no longer possible. An inspection of Figure 8.5 shows that this outer critical surface also contains a point where the effective gravity vanishes (i.e., the Lagrangian point L2). For a contact binary, the common stellar surface thus lies between the inner and outer critical surfaces corresponding to the equipotentials ^ = ^in and ^ = ^out.

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By definition, contact binary stars have both components filling or overfilling their Roche lobes. Practically all known contact systems are eclipsing binaries. The light curves of these extremely close systems have a sinusoidal appearance, which is due to the severe tidal distortion of the components. They also have eclipse minima of almost equal depth, implying very similar effective temperatures for both components. In fact, this property of the contact binaries seems to be continuous over a wide range of spectral types, from stars as early as O type to stars as late as K type. (They range in orbital period from 5.6 days to 0.22 days.) The similarity of effective temperatures would not be surprising if contact binaries consisted of identical stars. However, for some as yet unknown reason, these binaries always consist of dissimilar components with unequal masses. Note also that the components of contact binaries have luminosity ratios roughly equal to the first power of their mass ratio rather than the fourth power or so observed for single main-sequence stars.

Struve (1948) was the first to recognize that the anomalous mass-luminosity relation of the contact binaries might be causally related to the existence of a common envelope that redistributes and radiates away the luminosities emanating from the two independent cores. This important suggestion was further discussed by Osaki (1965), who pointed out that the radiative flux \F| is proportional to the effective gravity |g| in a common radiative envelope in mechanical equilibrium (see Eq. [3.41]). If this radiative flux is ultimately radiated away by the photosphere at the rate o Tf von Zeipel's law of gravity darkening thus implies that

where Teff is the effective temperature and g is the local surface gravity. Now, the condition that the free surfaceof acontact binarymust be an equipotential implies a relation between the radii and masses of the components. For the binary Roche model, this relation may be approximated by

It follows at once that the average surface gravities (^ GM/R2) of the two components are nearly equal. Hence, by virtue of Eq. (8.63), their effective temperatures should be also nearly equal.

The case of a common convective envelope in mechanical equilibrium was subsequently discussed by Lucy (1967), who found that the variation of effective temperature with local surface gravity is of the form

Again, because the average surface gravities of the two components are closely equal, this gravity-darkening law predicts little variation of effective temperature over the free surface of a late-type contact binary.

Following Osaki (1965) and Lucy (1968), we can now derive a theoretical mass-luminosity relation that is valid for both the early-

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type and late-type contact binaries. It follows at once from Eq. (8.64) that the ratio of surface areas (^ R2) of the two Roche lobes is closely equal to the mass ratio. Hence, because we have shown that the components of a contact binary have similar surface brightnesses (^ L/4nR2), we obtain the approximate relation

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This relation closely agrees with the observational data. We therefore conclude that the anomalous mass-luminosity relation of the contact binaries merely reflects the ratio of surface areas for components having similar effective temperatures.

It is generally accepted that the main features of the photosphere of a contact binary star are to be understood in terms of energy transport within a common (radiative or convective) envelope. The foregoing discussion clearly shows that the top layers of the common envelope are barotropic (with equal pressures, densities, and temperatures over the equipotentials). Yet, because the two underlying radiating cores have unequal masses, we know that the temperature distribution cannot be uniform over the Roche lobes. By continuity, temperature differences over each equipotential above the inner critical surface do exist, therefore implying that the bottom layers of the common envelope are baroclinic (see Section 3.2.1). We are thus faced at once with the following two questions: First, what is the exact nature of the energy flow that brings nearly equal effective temperatures in the two components of a contact binary? And, second, is it possible to build a common-envelope model that is barotropic in its outermost surface layers while being baroclinic near the two dissimilar Roche lobes?

As was pointed out by Lucy (1968), the paradox of overluminous secondaries in the late-type contact binaries can be resolved by assuming some lateral energy transfer in a common convective envelope. The existence of early-type contact binaries makes it clear that this energy transfer can occur even in contact binaries with radiative envelopes. This fact strongly suggests that there exists a transfer mechanism common to both the late-type and early-type contact binaries that is quite independent of the underlying envelope structure. This is the reason why it has often been conjectured that the required interchange of heat and mass is directly attributable to a lateral temperature or entropy gradient, in a direction roughly parallel to the equipotentials, near the base of the inner critical surface. For the sake of simplicity, I shall consider the case of a common radiative envelope.

In the frame rotating with the Keplerian orbital angular velocity Q, the basic equations governing the motion in an early-type contact binary are dp

— + u ▪ grad u + 2H x u = -- gradp + grad ^ + - F(u), (8.68)

Fourier Transform

P T ( — + u ▪ gradSj = div(x grad T) + peNuC, (8.69)

where u is the velocity relative to the rotating axis, F is the turbulent viscous force per unit volume, and ^ is the Roche potential defined in Eq. (8.62). Remaining symbols have their standard meanings (see Section 3.2). These six scalar equations are to be solved subject to appropriate initial and boundary conditions at the two stellar centers and at the top of the common envelope.

Numerous attempts have been made to build a contact-binary model consisting of two stars having different masses but equal effective temperatures. Yet, as is well known, the internal structure of a contact binary remains a puzzle. It is not my intention in this section to review all the conflicting models that can be found in the literature. Rather, I shall briefly comment on one important but often forgotten ingredient of the problem, namely, the geostrophic (or astrostrophic) flow that is required to prevent the appearance of unwanted discontinuities in the solutions. Since all proposed models do exhibit discontinuities at the base of the common envelope, astrostrophy could well provide the solution for the existing impasse.

We begin by describing the barotropic models originally proposed by Shu, Lubow, and Anderson (1976) because they may be viewed as the zeroth-order solution for unevolved main-sequence contact binaries. Following these authors, we make the a priori assumption that, apart for the slow thermally driven currents discussed in Chapter 4, the system is at rest in the corotating frame (i.e., u = 0). Since the condition of mechanical equilibrium is in general incompatible with the energy equation in a circulation-free barotrope, we must therefore assume that radiative equilibrium holds on average on each equipotential * = constant (see Sections 3.3.1 and 6.2). To derive the zeroth-order equations, we shall also introduce a system of curvilinear coordinates (£, n, Z) with % = * and with n and Z defining the "horizontal" position on a level surface. Assuming further that the chemical composition is uniform over each equipotential, one finds that p = p0(*), p = p0(*), and T = T0(*). Hence, letting u = 0 in Eqs. (8.67)-(8.69), we obtain dpo i87n d* = P0 (8J1)

in the radiative regions. As usual, L is the total luminosity, g is the effective gravity averaged over an equipotential, and A is the area of that closed surface. Similar ordinary differential equations can be written down for the two convective cores in which nuclear burning is taking place.

Since Eq. (8.62) gives a complete specification of the effective gravitational field, detailed solutions of these ordinary differential equations can be obtained using the standard boundary conditions at the two centers and at the shared surface. Unfortunately, as was correctly pointed out by Shu and coworkers, there are too many boundary conditions to satisfy for all thermodynamic variables to be continuous across the inner critical surface. Because mechanical requirements imply that the pressure p0(*) must be continuous across the Roche lobes, it was therefore concluded that no barotropic solutions with unequal stellar components exist unless one makes allowance for discontinuous changes in the density p0(*) and the temperature T0(*) at one of the Roche lobes. This is the contact-discontinuity hypothesis. Although the models constructed according to this idea look very much like observed contact binaries, they have been widely criticized on the ground that a contact discontinuity should disappear on a thermal time scale. * I shall not go into the disputes because, unsatisfactory as these zeroth-order barotropic models might be, they could provide the foundation for a more satisfactory solution of the basic equations.

* Lucy (1976) and others have suggested that a newly formed contact binary will evolve on a thermal time scale toward a state of marginal contact and that, if contact is then broken, the system will evolve back into contact, again on a thermal time scale. This is the thermal-relaxation-oscillation hypothesis.

As was pointed out by Shu (1980), however, a contact discontinuity will also naturally arise in these oscillatory models, with the zeroth-order barotropic models constituting the equilibrium states about which Lucy's (1976) models might undergo thermal relaxation oscillations.

Obviously, if the two stellar components had the same mass, their common envelope could be treated as a barotrope, all the way from the Roche lobes to the photosphere. Because the mass ratio is not in general equal to one, however, the luminosities generated in the two separate cores become necessarily unequal at the inner critical surface. This uneven distribution of the sources of heat generates a lateral interchange of heat and mass in the bottom layers of the common envelope. As we shall demonstrate, this inescapable fact implies the existence of a large-scale astrostrophic flow along the equipotentials that lie above the inner critical surface.

In Section 2.2.3 we have seen that the relative importance of the inertial and Coriolis effects is measured by the Rossby number Ro (= U/ QD), where U characterizes the scale of the horizontal velocity. In the present case, the Rossby number is of the order of the ratio of the orbital period (= 2n/ Q) to the characteristic time of the flow (^ D/U). Since this ratio is undoubtedly much smaller than one, the inertia of the relative motion can be neglected in Eq. (8.68). Hence, restricting attention to steady motions in the corotating frame, we can rewrite that equation in the form

Note that we have omitted the viscous force because it plays a negligible role away from the boundaries (see, however, below).

To present a self-consistent formulation of the problem, we shall first write each thermodynamic variable as the sum of the (known) zeroth-order solution and abaroclinic "correction." We thus let p = po(W) + pi(*; ), (8.74)

and we write similar expressions for the density and the temperature in the common envelope. Making use of Eq. (8.71), we can thus rewrite the "vertical" component of Eq. (8.73) in the form

where the subscript "V " designates a component along the effective gravity. Similarly, the two "horizontal" components of that equation are

where the subscript "H " designates a component parallel to the equipotentials.

The key point to our discussion is that the thickness d of the common envelope is much smaller than the typical horizontal length D, which is the mutual separation. Since the horizontal scale of variation of p1 is O(D), it readily follows from Eq. (8.76) that p1 = O(pQUD). Accordingly, because in Eq. (8.75) the vertical pressure gradient dp1/dW is O(p1/d), one finds that dp1/dW is O(pQUD/d). Taking into account that the vertical component of the Coriolis force is O(pQU), we obtain

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