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Atmospheres of components of the close binary stars

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Abstract. For theoretical modeling of binary systems, one has to consider realistic models which takes into account the radiative transfer, hydrodynamics, and the effect of irradiation from the secondary component on the atmosphere of primary component. Since the problem is complex, we studied in the thesis idealized models which will help us in understanding the important physical processes in close binaries. As a first step to understand the reflection effect we have developed a method of obtaining radiation field from the spherical surface irradiated by an external (i) point source (ii) extended source of radiation in close binary systems. The method has been extended in the case of atmospheres distorted due to self rotation of the component and tidal effects due to the presence of its companion. In all the cases we used two-level atom approximation with complete redistribution in calculating the spectral lines formed in the atmosphere of the primary star. The effects of irradiation from the secondary component on the atmosphere of the primary is calculated depending upon the geometrical shape of the illuminated surface, proximity of the secondary component to the primary and ratio of the luminosities of the primary and the secondary. We calculated the line profiles with various parameters like density and velocity variations.

We notice that the expansion of the medium produces P Cygni type profiles and the irradiation enhances the emission in the lines although the equivalent widths reduce considerably. In the case of rotationally distorted star without tidal forces we find the radiation to be diluted. Close binary systems with tidal distortion produce emission profiles filling the self absorption from the primary component.

Keywords : radiative transfer – close binaries -reflection effect

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1. Introduction

Binary stars are of fundamental importance in astrophysics for (i) more than 50% of all stars are in such systems (often in close ones, in which mutual illumination cannot be neglected) (ii) the masses of the components can be determined essentially from their orbital motion, and (iii) there are often flows of matter from one component to the other that give rise to a variety of interesting phenomena like accretion discs, reflection effect etc.

Unfortunately, the detailed understanding of the physical properties of close binaries is still incomplete since their structure is extremely complicated. In particular, (i) the radiation fields are no longer one-dimensional as those of single stars or of wide pairs, (ii) the shapes of the stars making up the binary are no longer spherical, and (iii) the energy balance becomes much more involved than that of classical atmospheres, since meridional circulations are induced. The present thesis addresses problems of the outer layers of such stars with the emphasis on problems of radiative transfer.

The atmosphere of a star with close companion is influenced by two interaction mechanisms. The gravitational interaction results in a distortion of the outer layers of the star. The radiative interaction results in a warming of those surface layers of the star nearest the companion and gives rise to the "reflection effect". Calculations have been undertaken with the intention of describing the influence of a close companion on the spectrum of the star as seen by distant observer. The details of some of the results can be found (Peraiah & Srinivasa Rao 1998, Srinivasa Rao & Peraiah 2001).

2. Calculation of self radiation of primary star

Case 1: The equation of radiative transfer in a spherically symmetric medium for incoming and outgoing ray (Peraiah, 1984)is given by,

$$\pm\mu\frac{\partial \mathbf{U}(r,\pm\mu)}{\partial r} \pm \frac{1}{r}\frac{\partial}{\partial\mu}[(1-\mu^2)\mathbf{U}(r,\pm\mu)] + \sigma(r)\mathbf{U}(r,\pm\mu)$$
$$= \sigma(r)\left[[1-\omega(r)]\mathbf{B}(r) + \frac{1}{2}\omega(r)\int_{-1}^{+1} p(r,\pm\mu,\mu')\mathbf{U}(r,\mu')d\mu'\right], \qquad (1)$$

where $\mu = \cos\theta$ (is the cosine of the angle made by the ray with radius vector), is in the interval [0, 1], $\omega(r)$ is the albedo for single scattering, $U(r,\mu)$ is the specific intensity of the ray, r is the radius, $\sigma(r)$ is the absorption coefficient, B(r) represents the sources inside the cell, and $p(r,\mu,\pm\mu')$ is phase function normalized to 1.

Case 2: Equation of line transfer in the comoving frame with absorption and emission due to dust and gas for incoming and outgoing ray (Mihals, D, et. al, 1975, Peraiah, A., et. al., 1987) is given by,

$$\begin{aligned}
\pm\mu\frac{\partial I(x,\pm\mu,r)}{\partial r} &\pm \frac{(1-\mu^2)}{r}\frac{\partial I(x,\pm\mu,r)}{\partial\mu} \\
&= K_L(r)\Big[(\phi(x)+\beta)\Big]\Big[S(r,\mu,x)-I(r,\pm\mu,x)\Big] \\
&\quad+\left[(1-\mu^2)\frac{V(r)}{r}+\mu^2\frac{dV(r)}{dr}\right]\frac{\partial I(r,\pm\mu,x)}{\partial x} \\
&\quad+K_{dust}\Big[S_{dust}(r,x)-I(r,\pm\mu,x)\Big], \qquad (2)
\end{aligned}$$

where $I(x,\pm\mu,r)$ is the specific intensity of the ray at an angle $\cos^{-1}\mu$ ($\mu=(0,1)$) with the radius vector at the radial point r, with frequency $x(=(\nu-\nu_o)/\Delta\nu_D$ where ν_o and ν are the frequency points at the line centre and at any point in the line and $\Delta\nu_D$ is the standard frequency interval such as Doppler width), $V(r)$ is the velocity of the gas at r in mean thermal units (mtu). Here $K_L(r)$ is the line-centre absorption coefficient, β is the ratio of continuum to the line opacities. $\phi(x)$ is the profile function subjected to normalization. The effect of velocity is taken into account during the transformation from comoving frame to obsever's frame. The profile function is given by

$$\phi(x)=\frac{1}{\delta\sqrt{\pi}}e^{\left[-\left(\frac{x}{\delta}\right)^2\right]}, \qquad (3)$$

where δ is the Doppler width. Here we assumed a Doppler profile function. The quantity $S(r,x)$ is the source function given by,

$$S_s(r,x))=\frac{\phi(x)}{\beta+\phi(x)}S_L(r)+\frac{\beta}{\beta+\phi(x)}S_c(r,x), \qquad (4)$$

and

$$S_L(r,x)=\frac{(1-\epsilon)}{2}\int_{-\infty}^{+\infty}\phi(x)dx\int_{-1}^{+1}I(r,\mu',x)dxd\mu'+\epsilon B(x,T(r)), \qquad (5)$$

is the line source function. The quantity $S_c(r)$ is the continuum source function given by,

$$S_c(r)=\rho(r)B(x,T(r)). \qquad (6)$$

Here ϵ is the probability per each scattering that a photon is destroyed by collisional de-excitation. $\rho(r)$ is a dilution factor and $B(x,T(r))$ is the Planck function with frequency x, and temperature T at the radial point r. $K_{dust}(r)$ is the absorption coefficient of the dust and the dust source function $S_{dust}(r,x)$ is given by,

$$\begin{aligned}
S_{dust}(r,x) &= (1-\omega)B_{dust}+ \\
&\quad\frac{\omega}{2}\int_{-\infty}^{+\infty}\delta(x-x')dx'\int_{+1}^{-1}P(\mu,\mu',r)I(r,\mu',x)d\mu', \qquad (7)
\end{aligned}$$

where $\delta(x - x')$ is the Dirac delta function, B_{dust} is the Planck function for the dust emission, ω the albedo of the dust and P is the isotropic scattering phase function. The quantity B_{dust} is normally neglected because the re-emission will be far away from the line centre and therefore may not contribute to the line radiation. Although we need not consider the term containing B_{dust}, we have included it for the sake of completeness.

We have adopted the "CELL" method described by Peraiah (1984) to solve the above equations and the calculation of line profiles for an observer at infinity. These solutions are developed using Discrete space theory of radiative transfer and are used to calculate self radiation of the primary star in a binary system Peraiah (1984).

3. Calculation of irradiation from secondary star

3.1 Distribution of emergent radiation along the line of sight when incident radiation is from point source

We have shown in figure 1 the portion of the star illuminated by radiation from a point source X. The atmosphere is divided into several shells of equal radial thickness. The radiation from this irradiated part of the atmosphere is received by the observer at infinity. We have chosen a set of parallel rays tangential to the shell boundaries at a point on the axis OX where O is the centre of the component. Let one of these rays meet the shell boundaries at $Q_1, Q_2, Q_3, \ldots$ etc. The intensity along the parallel rays is calculated first by obtaining combined source functions (self+irradiated) at points $Q_1, Q_2, \ldots$ etc.

For this purpose we have (1) the source function at these points due to self-radiation described in case 1, S_s and (2) source function due to irradiation S_I. The latter is calculated by using rod model Peraiah (1982). The radiation field is calculated along the lines $Q_1P_1, Q_2P_2, Q_3P_3 \ldots$ etc. We then add the two source functions to obtain the total source function S_T.

$$S_T = S_s + S_I. \tag{8}$$

3.2 Calculation of line profiles when radiation is incident from an extended source

The geometry of the model is shown in figure 2 in which O and O′ are the centres of the primary and secondary respectively. The atmosphere of the primary is divided in to several shells. We would like to calculate the effect of irradiation from the secondary on the distribution of radiation field in the part of the atmosphere of the primary facing secondary. We have considered a set of rays along the line of sight and tangential to the shell boundaries at the points where the axis OO′ intersect them. We estimate the

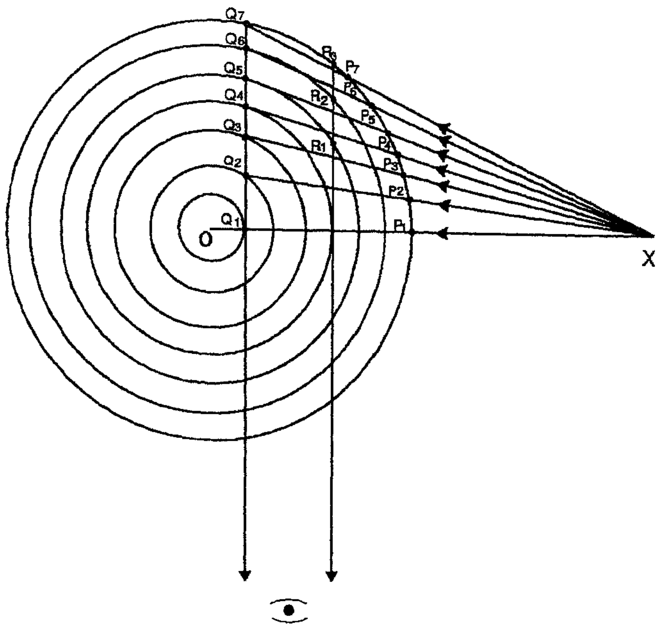

Figure 1. Schematic diagram showing the irradiated section of the component. X is the point source of radiation. O is the center of the component. The specific intensities are calculated along the line of sight

radiation field at points such as P where the parallel rays meet the shell boundaries. The radiation field at P is calculated by estimating the source function at P due to the radiation incident at P from the surface SW of the secondary facing the primary. We have selected a number of rays from SW incident on the atmosphere and entering the surface at points as $T, \tau, \ldots$ etc. We calculate the ray paths PT, $P\tau, \ldots$ etc., and optical depths along the rays. Using these optical depths, the specific intensities and source functions at the point P due to irradiation from the secondary can be calculated. Now we solve the equation of radiative transfer in spherical symmetry and obtain the source function S_s due to self radiation described in case 2.

3.3 Calculation of radiation field in a distorted surface

Let x be the ratio of angular velocities at the equator and pole, f is the ratio of centrifugal to gravity forces at the equator, $\frac{m_2}{m_1}$ the mass ratio of the two components and $\frac{r_e}{R}$ the ratio of the radius at the equator to the separation between the centre of gravity of the two components of a binary star system. We obtain the equation of the distorted surface

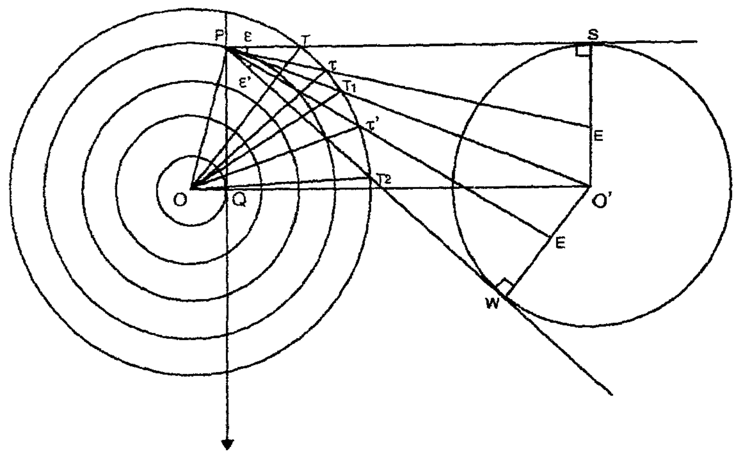

Figure 2. Schematic diagram of model reflection of radiation from the extended surface of the secondary

by solving a seventh degree equation which contains the above parameters (Peraiah 1969, 1970),

$$\alpha\rho^7 \sin^6\theta + \beta\rho^5 \sin^4\theta + \Big(\gamma \sin^2\theta + J\Big)\rho^3 - \Big(1 - Q\Big)\rho + 1 = 0, \tag{9}$$

where

$$J = Q\Big(3\sin^2\theta\cos\phi - 1\Big),$$

and θ and ϕ are the colatitude and the azimuthal angles respectively. Further, $\rho = \frac{r}{r_p}$, where r is the radius at an arbitrary point on the distorted surface and r_p is the radius at the pole

$$\alpha = \frac{f(x-1)^2}{6x^2}\left(\frac{r_p}{r_e}\right)^7 \; ; \qquad \beta = \frac{f(x-1)^2}{2x^2}\left(\frac{r_p}{r_e}\right)^5 \; ;$$

$$\gamma = \frac{f}{2x^2}\left(\frac{r_p}{r_e}\right)^3 \quad ; \quad Q = \frac{1}{2}\mu\left(\frac{r_p}{r_e}\right)^3 \quad ; \quad \mu = \frac{m_2}{m_1}\left(\frac{r_e}{R}\right)^3,$$

The ratios $\frac{r_p}{r_e}$ can be obtained from a third degree equation given by,

$$\left(\frac{r_e}{r_p}\right)^3 - u\left(\frac{r_e}{r_p}\right)^2 - \frac{1}{2}\;\mu = 0, \tag{10}$$

where

$$u = 1 + \frac{f\left(x^2 + x + 1\right)}{6x^2} + \mu.$$

Equation (10) is solved for various values of θ and ϕ for obtaining the surface for a given parameter set of $\frac{m_2}{m_1}$, f, x and $\frac{r_e}{R}$. The solution is obtained by using numerical methods with a starting value of $\frac{r}{r_p}$=1. Equation (10) is solved by Newton-Raphson method.

Transfer of line radiation is studied in such asymmetric atmosphere assuming complete redistribution and a two-level atom approximation. The atmosphere is assumed to be expanding radially. Various black body temperatures are being used to describe the total luminosity of the components (see Peraiah, Srinivasa Rao 2001) for the purpose of irradiation.

4. Results

When irradiation is from a point source we found that maximum radiation comes from intermediate points of the atmosphere, the reason being that we have combined radiation from the star together with the incident radiation from a point source outside the star.

We extended the method for calculating the radiation field on the primary component when secondary component is an extended source. We find that the reflection gradually decreases from the primary component towards the surface of the outermost layers of the atmosphere, since the medium is illuminated uniformly, the intensities decreasing from inner radius to the outer radius of the star.

When the separation between two components is decreased by a factor of 2 the equivalent width reduces by 50% due to the increase in the irradiation. This result holds good even when velocities are present in the medium which shows that geometry effect is more dominant.

Scattered radiation from dust fills up the absorption lines making them shallower. When the separation between binary components become less, the calculated absorption and emission peaks in P-Cygni type of profiles are also reduced in the presence of macroscopic motion.

In the case of distorted surface the self radiation produces absorption profiles while the incident radiation produces emission profiles and the combination of the self and incident radiation produces emission profiles when secondary component is a point source.

In an expanding atmosphere it is found that the absorption features produced due to self radiation may vanish and emission profile will appear when atmosphere is irradiated. There are perceptible changes noticed with variation of different parameters like density, velocity, mass ratio, etc.

5. Future work

We would like to calculate light curves of close binary systems considering multiple reflections (primary component heats the secondary component and secondary component heats the primary component) and Roche geometry.

We also would like to consider the reflection effect in 3-D geometry which is a more realistic model than the one considered in our study so far.

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