The energy transfer and its effects on the secondaries in W Ursae Majoris-type contact binaries

Dengkai Jiang$^{1,2}$*, Zhanwen Han$^1$, Tianyu Jiang$^{1,2}$, and Lifang Li$^1$

$^1$National Astronomical Observatories, Yunnan Observatory, Chinese Academy of Sciences, P.O. Box 110, Kunming, Yunnan Province, 650011, P.R. China
$^2$Graduate University of Chinese Academy Sciences, Beijing, 100039

ABSTRACT
Based on the physical parameters of 133 W Ursae Majoris (W UMa)-type contact binaries, the energy transfer and its effects on the secondary in W UMa contact binaries are investigated. Relations are given between the mass ratio ($q$) for W UMa contact binaries and the relative energy transfer rates, i.e. $U_1$, the ratio of the transferred luminosity to the surface luminosity of the primary and $U_2$, the ratio of the transferred luminosity to the nuclear luminosity of the secondary. The theoretical curves ($U_1$ vs $q$ and $U_2$ vs $q$) are derived based on the various assumptions that the two components in each W UMa system are nearly identical in effective temperature, they just fill their inner Roche lobes, and the primaries are ZAMS stars. Although these curves can reflect the distribution of $U_1$ vs $q$ and $U_2$ vs $q$, some observational systems are significantly deviated from these curves. It is mainly resulted from the difference in the effective temperatures of the components in W UMa systems. The radius and the density of the secondary are related to the relative energy transfer rate $U_2$: the higher is $U_2$, the greater is the expansion and the lower is the density of the secondaries in W UMa systems. In addition, it is found that the temperature difference of W UMa binary components is correlated with the relative energy transfer rate $U_1$ and decreases with increasing $U_1$. This might suggest that there is a thermal coupling between two components in W UMa contact binaries, and that the classification of W UMa contact binaries into A- or W-types depends on the energy transfer from the primary to the secondary. The temperature difference of W UMa binary components is poorly correlated with the mass of the primary. This suggests that the properties of the common envelope of W UMa contact binaries might not have a significant effect on the energy transfer between two components.

Key words: binaries: eclipsing – stars: statistics– stars: evolution

1 INTRODUCTION
W UMa contact binaries are very common eclipsing variables in which the eclipsing light curves have nearly equal minima. Binnendijk (1970) classified W UMa contact binaries into A- or W-type on the basis of their light curves. The secondaries of W UMa contact binaries have an unusual mass-luminosity relationship which was first recognized by Struve (1948). Lucy (1968) proposed that it is caused by the energy transfer from the primary (the more massive component) to the secondary (the less massive component) within a convective envelope. But the mechanism causing energy transfer between the two components of W UMa contact binaries and the effect of the energy transfer on the components are not clear.

W UMa contact binaries are an important class of eclipsing variables in several respects. In studies of Galactic structure, W UMa contact binaries play an important role because they have high spatial frequency of occurrence, ease of detection, and provide a standard candle for distance determinations (Rucinski 1997). More importantly, W UMa contact binaries are interesting objects due to the mass and energy transfer between two components. Understanding the energy and mass transfer in the common envelope is necessary to develop a correct theory of the structure and evolution of W UMa systems. Therefore, the investigation of the mechanism causing energy transfer is a core problem for understanding the structure and evolution of W
UMa contact binaries (Webbink 2003). The energy transfer in W UMa systems has been investigated by many authors (Mochnacki 1981, Smith 1984, Kaluzny 1984, Hilditch 1988). Mochnacki (1981) calculated the relative energy transfer rate of W UMa contact binaries using the normal mass-luminosity relation for independent stars and found that the relative energy transfer rate depends only on the mass ratio of W UMa contact binaries. Wang (1994) found that the relative energy transfer rate increases with increasing mass ratio continuously based on 22 contact binaries. Liu & Yang (2004) found that the energy transfer rate depends not only on the mass ratio but also on the evolutionary degree of the primary. By studying a catalogue data of 159 systems, Csizmadia & Klagyivik (2004) found that the energy transfer rate is a function of the mass and luminosity ratio.

The treatment of the energy transfer is very important to construct theoretical models of W UMa contact binaries. Although it seems probable that the energy transfer occurs in the common envelope of W UMa systems, it is not clear at present where and how the transfer is taking place in the common envelope. The structure and evolution of W UMa contact binaries have been investigated by several authors in recent years (Kühn 2002a, b; Li, Han & Zhang 2004, 2005; Yakut & Eggleton 2003). It is found that loss of contact is avoided if the energy transfer is assumed to be sufficiently effective (Kühn 2002a, b; Li, Han & Zhang 2004) discussed the region of energy transfer in the common envelope of W UMa contact binaries, and showed that the energy transfer may take place in the radiative region of the common envelope. Yakut & Eggleton (2005) suggested that the mechanism of the energy transfer may be differential rotation which has been observed by helioseismology in the solar convection zone (Schou et al. 1998).

The energy transfer from the primary to the secondary in W UMa contact binaries will restructure the secondary and make it oversized and over-luminous for its mass (Webbink 2003). The radii of the secondaries of W UMa contact binaries (including A- and W-types) are obviously altered from those of zero-age main sequence (ZAMS) stars (Yakut & Eggleton 2003; Li et al. 2008). This might be the result of the energy transfer from the primary to the secondary (Yang & Liu 2001; Li et al. 2008). The temperatures and densities of the secondaries of W UMa contact binaries are also affected by the energy transfer. Hazlehurst et al. (1974) calculated the response functions which describe the effect of energy transfer on the radii and effective temperatures of the stars. But the relation between the energy transfer and the reaction of the secondaries of W UMa systems is not completely understood.

In this paper, the physical parameters of 133 W UMa contact binaries have been collected from the literature. Using these data, the energy transfer and its effect on the secondaries in W UMa systems are investigated.
Using equation (1), we have luminosities, respectively (Mochnacki 1981; Wang 1996) that the primaries are ZAMS, the relative energy transfer rate which is indeed different from Roche approximation relation. According to equation (8), the theoretical curves and the observational data are shown in Figure 2 and Figure 3 with a solid line and the open stars (W-subtypes) or the solid squares (A-subtypes), respectively. It is seen in Figure 2 and Figure 3 that although the theoretical curves can reflect the distribution of the $U_1$ vs $q$ and $U_2$ vs $q$ of the observed data, the observational points are largely scattered and some observed systems are significantly deviated from the solid line. The deviation might be caused by the applicability of the basic assumptions.

In order to find the applicability of the basic assumptions, we take $r$, $t$, and $\alpha$ to be different values. At first, we must inspect the applicability of a basic assumption that the components of each W UMa system just fill their inner Roche lobes (i.e. $R_2/R_1 = q^{0.46}$). In fact, most observed systems are over-contact binaries, and they should not satisfy this relation. The relation between the logarithms of the radius ratio ($R_2/R_1$) and the logarithms of the mass ratio $q$ of the observed systems is shown in Figure 4. As seen from Figure 4, the logarithm of the radius ratio is almost linearly changed with the logarithms of the mass ratio. A least-squares solution leads to the following relation,

$$\log(R_2/R_1) = 0.431(6)\log q - 0.007(3).$$  \hfill (8)

According to equation (8), $r = R_2/R_1 = 0.984q^{0.43}$, which is indeed different from Roche approximation relation $r = q^{0.46}$. These relations are also plotted in Figure 4 with a dashed line and a solid line, respectively. Using the relation, $r = R_2/R_1 = 0.984q^{0.43}$, of the observed systems, equation (4) and equation (5) are shown in Figure 2 and Figure 3 with a dot-

### Table 1. The new or recently obtained physical parameters of contact binaries.

| Stars     | Type | $P$ (days) | $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $R_1$ ($R_\odot$) | $R_2$ ($R_\odot$) | $L_1$ ($L_\odot$) | $L_2$ ($L_\odot$) | $T_1$ (K) | $T_2$ (K) | $q_{ph}$ | References |
|-----------|------|------------|-------------------|-------------------|-------------------|-------------------|------------------|------------------|-----------|-----------|----------|-------------|
| VW LMi    | W    | 0.4775     | 1.67              | 0.70              | 1.709             | 1.208             | 5.31             | 2.80             | 6700      | 6792      | 0.416    | 1           |
| BX Dra    | A    | 0.5790     | 2.19              | 0.63              | 2.13              | 1.26              | 9.8              | 2.5              | 7000      | 6446      | 0.289    | 1           |
| DN Bootis | A    | 0.4476     | 1.428             | 0.148             | 1.710             | 0.67              | 3.750            | 0.560            | 6095      | 6071      | 0.103    | 2           |

Columns: Stars-GCVS name of star; $P$-orbital period; $M_1$-mass of the primary; $M_2$-mass of the secondary; $L_1$-luminosity of the primary; $L_2$-luminosity of the secondary; $R_1$-radius of the primary; $R_2$-radius of the secondary; $T_1$-effective temperature of the primary; $T_2$-effective temperature of the secondary

References in Table 1: (1) Sánchez-Bajo et al. 2007; (2) Şenavcı et al. 2008

$U_2$ vs $q$ of the observed data, the observational points are largely scattered and some observed systems are significantly deviated from the solid line. The deviation might be caused by the applicability of the basic assumptions.

$$U_2 = \log\left(\frac{r^2t^4 - q^\alpha}{q^\alpha(1 + r^2t^4)}\right).$$  \hfill (5)

where $r = R_2/R_1$, $t = T_2/T_1$, $q$ is mass ratio and $\alpha$ is the exponent of mass-luminosity relation and it is equal to 3.42. If it is assumed that the components in each W UMa system are identical in the effective temperature, and that the components of each W UMa contact binary just fill the inner Roche lobes (i.e. $R_2/R_1 = q^{0.46}$), equation (4) and equation (5) can be written as

$$U_1 = \frac{0.92 - q^{3.42}}{1 + q^{3.42}}.$$  \hfill (6)

$$U_2 = \log\left(\frac{q^{0.92} - q^{3.42}}{q^{3.42}(1 + q^{0.92})}\right).$$  \hfill (7)

In these systems, three high-mass systems (AC Boo, ET Leo and V899 Her) with total mass larger than $2M_\odot$ are below the solid line. This kind of deviation can be caused not only by the presence of the additional companions, but also by the evolved components contained in these systems. In fact, Bilir et al. (2005) found that low-mass W UMa contact binaries and low-mass W UMa systems have a larger mean kinematic age than high-mass W UMa systems, implying that some components of W UMa contact binaries with very low total masses are significantly evolved. On the other hand, Pribulla & Rucinski (2006) found that up to 59 percent of W UMa contact binaries have companions. Meanwhile, Pribulla et al. (2008) show that TZ Boo is quadruple system and its spectra is contaminated by third and fourth bodies. Therefore, the effect of the companions on the spectroscopic solution of these systems might be one of the reasons which lead these systems to deviate significantly from the solid line.

Mochnacki (1981) defined a relative energy transfer rate which is the ratio of the transferred luminosity to the surface luminosity of the primary. Based on the assumption that the primaries are ZAMS, the relative energy transfer rate $U_1$ can be written as

$$U_1 = \frac{dL}{L_1} = \frac{\frac{L_2}{L_1} - \frac{L_2}{L_2}}{1 + \frac{L_2}{L_2}}.$$  \hfill (2)

where $L_{1,2}$ are the surface luminosity of the primary and the secondary; $L_{10}$ and $L_{20}$ are their nuclear luminosities, respectively (Mochnacki 1981; Wang 1994). We can give another relative energy transfer rate as

$$U_2 = \log\left(\frac{dL}{L_{20}}\right) = \log\left(\frac{\frac{L_2}{L_2} - \frac{L_2}{L_2}}{\frac{L_2}{L_2}(1 + \frac{L_2}{L_2})}\right).$$  \hfill (3)

Using equation (1), we have

$$U_1 = \frac{r^2t^4 - q^\alpha}{1 + q^\alpha},$$  \hfill (4)

$viate strongly from the line and the corresponding systems with $\left[\log(L_1 + L_2) - \log(L_{10} + L_{20})\right] > 0.4$ are listed in Table 2.

The theoretical curves and the observational data are shown in Figure 2 and Figure 3 with a solid line and the open stars (W-subtypes) or the solid squares (A-subtypes), respectively. It is seen in Figure 2 and Figure 3 that although the theoretical curves can reflect the distribution of the $U_1$ vs $q$ and $U_2$ vs $q$ of the observed data, the observational points are largely scattered and some observed systems are significantly deviated from the solid line. The deviation might be caused by the applicability of the basic assumptions.
Table 2. Physical parameters of most discrepant contact binaries.

| Stars   | Type | P (days) | M₁ (M☉) | M₂ (M☉) | R₁ (R☉) | R₂ (R☉) | L₁ (L☉) | L₂ (L☉) | T₁ (K) | T₂ (K) | qₚh  | References |
|---------|------|----------|----------|----------|---------|---------|---------|---------|--------|--------|------|------------|
| AC Boo  | W    | 0.3524   | 1.534    | 0.476    | 1.314   | 0.572   | 1.427   | 0.269   | 5530   | 5520   | 0.31 | 1           |
| V1073 Cyg | A    | 0.7859   | 1.498    | 0.479    | 2.154   | 1.318   | 8.263   | 3.020   | 6700   | 6661   | 0.320 | 1           |
| ET Leo  | W    | 0.3465   | 1.586    | 0.542    | 1.359   | 0.835   | 1.115   | 0.564   | 5112   | 5500   | 0.342 | 2           |
| V899 Her | A    | 0.4212   | 2.1      | 1.19     | 1.57    | 1.22    | 2.32    | 1.44    | 5700   | 5677   | 0.566 | 3           |
| TZ Boo  | A    | 0.2976   | 0.72     | 0.11     | 0.97    | 0.43    | 1.02    | 0.18    | 5890   | 5754   | 0.153 | 4           |
| BH Cas  | W    | 0.4059   | 0.73     | 0.35     | 1.09    | 0.78    | 1.01    | 0.72    | 5550   | 6000   | 0.475 | 5           |
| XY Boo  | A    | 0.3706   | 0.912    | 0.169    | 1.230   | 0.607   | 2.138   | 0.515   | 6324   | 6307   | 0.1855 | 6          |
| DX Tuc  | A    | 0.3771   | 1.00     | 0.30     | 1.20    | 0.71    | 1.97    | 0.66    | 6250   | 6182   | 0.29  | 7           |

Columns: Stars-GCVS name of star; P-orbital period; M₁-mass of the primary; M₂-mass of the secondary; L₁-luminosity of the primary; L₂-luminosity of the secondary; R₁-radius of the primary; R₂-radius of the secondary; T₁-effective temperature of the primary; T₂-effective temperature of the secondary

References in Table 1: (1) Awadalla & Hanna 2005; (2) Gazeas et al. 2006; (3) Özdemir et al. 2002; (4) Yakut et al. 2005; (5) Zola et al. 2001; (6) Yang et al. 2005; (7) Szalai et al. 2007

Figure 2. The relative energy transfer rate $U₁$ as a function of mass ratio of W UMa contact binaries. The symbols are the same as Figure 1 and these curves are derived from the assumptions (see the text).

Figure 3. The relative energy transfer rate $U₂$ as a function of mass ratio of W UMa contact binaries. The symbols are the same as Figure 1 and these curves are derived from the assumptions (see the text).
Figure 4. Relation between log($R_2/R_1$) and log($q$) for A- and W-type W UMA contact binaries. Full squares and open stars represent A-types and W-Types, respectively. The solid line represents log($R_2/R_1$) = 0.43log($q$). The dash line represents the fitted curve and the symbols are the same as Figure 1.

Figure 5. Relations between the temperature difference and the relative energy transfer rate $U_1$ for A- and W-type W UMA contact binaries. The symbols are the same as Figure 1.

Figure 6. The distribution of temperature deviation vs the mass of primary for W UMA contact binaries. The Symbols are the same as Figure 1 and $M_1$ is in solar mass.

Figure 7. The relations between the relative radius change of the secondary and the relative energy transfer rate $U_2$ for A- and W-type W UMA contact binaries, and the solid line represents the linear fit. Symbols are the same as Fig.1.

Rucinski (1974) investigated the relations between the temperature difference and other observational parameters, and found that the temperature difference for W-type systems is not correlated with the mass ratio, the fill-out parameter or the color.

The relation between the relative energy transfer rate ($U_1$) and the temperature difference is shown in Figure 5. W UMA contact binaries seem to populate a strip limited by two solid lines, and there is a tendency for decreasing temperature difference with increasing relative energy transfer rate. This suggests that the temperature difference is correlated with the relative energy transfer rate ($U_1$). This also indicates that the temperature of the secondary increases with increasing relative energy transfer rate and even exceeds the temperature of the primary if the relative energy transfer rate ($U_1$) is large enough, and that a thermal coupling exists in the two components of W UMA contact binaries.

Main-sequence stars with $M \gtrsim 1.25M_\odot$ have a convective envelope and a radiative core (Hurley et al. 2000). Li, Han & Zhang (2004) argued that convection is by no means essential to heat transport in the common envelope of W UMA systems by employing Eggleton’s stellar evolution code (Eggleton 1971, 1972, 1973). This means that the temperature difference should not depend on the mass of the primary. The distribution of the temperature difference $X$ vs the primary’s mass $M_1$ is shown in Figure 6. As seen from Figure 6, the distribution of temperature difference of the observed systems with $M_1 \gtrsim 1.25M_\odot$ is similar to that of the systems with $M_1 \lesssim 1.25M_\odot$. This suggests that there is no correlation between the temperature difference and the mass of the primary, and that the efficiency of energy transfer in the common envelope of W UMA systems is indeed not significantly enhanced by convective motion.
3 THE EFFECT OF ENERGY TRANSFER ON THE SECONDARIES

The mass-radius relations of the secondaries for A- and W-type of W UMa contact binaries are different from that of ZAMS stars (Yang & Liu 2001; Awadalla & Hanna 2005; Li et al. 2008). This is a result of the energy transfer from the primary to the secondary (Webbink 2003; Li et al. 2008). But the relation between the energy transfer and the radius of the secondary is not clear.

The relation between the relative radius change of the secondary (log(dR2/R20) = log((R2 - R20)/R20)) and the relative energy transfer rate (U2) of W UMa contact binaries is plotted in Figure 7. R20 is the radius of the main sequence secondary in W UMa systems without the effect of the energy transfer, i.e. it is the radius of ZAMS with mass M2. According to Lacy (1977), it can be expressed as

\[ R_{20} = \begin{cases} 0.955M_2^{0.17} & 0.1 \leq M_2 \leq 1.318, \\ 1.026M_2^{0.640} & 1.318 \leq M_2 \leq 19.953, \end{cases} \quad (10) \]

where M2 is the mass of the secondary in solar units. As seen in Figure 7, the relative radius change of the secondary is correlated with the relative energy transfer rate U2, i.e. the radius of the secondary in a W UMa system increases with increasing U2. This indicates that the energy transfer exercises a decisive influence on the secondaries of A-type and W-types. By using a linear fitting, the relation between the relative radius change of the secondary (log(dR2/R20)) and the relative energy transfer rate (U2) can be written as

\[ \log(dR_2/R_{20}) = 0.41(1)U_2 - 0.56(2). \quad (11) \]

This correlation is a result of the response of the secondary to the energy transfer from the primary. It is the energy transfer that makes the radii of the secondaries of W UMa contact binaries deviate from those of ZAMS stars (Yang & Liu 2001; Li et al. 2008). However, a W UMa system VW Cep has a radius smaller than that given by equation (10). VW Cep is one of triple systems (Pribulla & Rucinski 2006). So the smaller secondary of VW Cep might be attributed to an inaccurate spectroscopic solution due to the presence of the additional companion.

4 DISCUSSION AND CONCLUSIONS

In this paper, we investigate the energy transfer of W UMa contact binaries based on a sample of 133 W UMa contact binaries, and then we study the effects of the energy transfer on the secondaries of W UMa systems.

Based on the assumptions (the components are contact configurations with nearly uniform effective temperature and the primaries are ZAMS), the relations are given between the relative energy transfer rates and the mass ratio of W UMa systems. The theoretical curves can reflect the distribution of U1 vs q and U2 vs q. But some observation systems are significantly deviated from these curves. By comparing the observational data and these resulting curves, it is found that the deviations are mainly resulted from the difference in the effective temperatures of the components in W UMa systems. This means that the assumption that the components are uniform in effective temperature should be restrainedly applied to investigate the energy transfer in W UMa systems.

The distribution of the temperature difference vs the mass of the primary suggests that the convection does not affect the efficient of energy transfer between two components in the common envelope of W UMa contact binaries. This suggests that the energy transfer in W UMa systems does not depend on the property of the common envelope of W UMa contact binaries and the convection is by no means essential to heat transport in the common envelope of W UMa systems. This also suggests that the energy transfer might occur in radiative region of common envelope of W UMa contact binaries (Li, Han & Zhang 2004) or the mechanism of energy transfer might be the differential rotation (Yakut & Eggleton 2005) or circulation currents (Webbink 1977; Robertson 1980, and references therein).

The energy transfer from the primary to the secondary would lead W UMa systems to be not in thermal equilibrium, then lead W UMa contact binaries to suffer thermal relaxation oscillations (TRO). However, the energy transfer is also related to the evolutionary degree of the primary, i.e. the higher is the evolutionary degree of the primary, the lower is the energy transfer rate (Liu & Yang 2004). This suggests that with the evolution of W UMa systems, the thermal relaxation oscillation might be disappeared if the
evolutionary degree of the primary is high enough. If the energy transfer rate decreases in the evolved W UMa sys-
tems, the rate of mass transferred from the secondary to the primary should become smaller and smaller with the evo-
lution of W UMa systems, and the decrease in mass ratio of the systems would become slower and slower, so that the lifetime of W UMa systems might become longer than the prediction of the theory models (Li, Han & Zhang 2005).

Figure 7 shows that the relative radius change of the secondary increases with increasing relative energy transfer rate $U_2$. Webbink (2003) and Li et al. (2008) suggested that the the deviation of the radius of the secondary from that of ZAMS stars is probably the result of the energy transfer from the primary to the secondary in W UMa contact binaries. The energy transfer from the primary to the secondary is more than the energy generated in the core of the secondary, so the radius and density of the secondaries is significantly influenced by the energy transfer and their radius and density deviates from those of ZAMS stars. Hazlehurst et al. (1977) calculated the effects of energy transfer on the radius and temperature of stars and gave the response functions for the radius and temperature of the stars. In present paper, we have given a relation between the relative radius change of the secondary and the relative energy transfer rate $U_2$. This relation probably provides a useful information in the structure of the secondaries in W UMa contact binaries, and can help us to understand the structure and evolution of W UMa systems.

ACKNOWLEDGEMENTS

The authors are grateful to an anonymous referee for his/her valuable suggestions and insightful remarks, which have improved this paper greatly. This work was partly supported by the Chinese Natural Science Foundation (10673029, 10773026, 10433030 and 10521001), and by the Yunnan Natural Science Foundation (2007A113M and 2005A0035Q).

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