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A Possible Explanation of the O'Connell Effect in Close Binary Stars *

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Abstract A theoretical model for explaining the O'Connell effect of close binary stars is given based on the hypothesis that the circumstellar material of a binary system is captured by its components. The results inferred from the model suggest that late-type and/or short-period binaries can easily produce obvious O'Connell effect and that the occurrence of O'Connell effect has no relation with the type of binaries. These conclusions are in agreement with the observed results. The observed O'Connell effects of six binary systems are examined by the model. For three W-subtype W UMa binaries (YY Eri, BX Per and SW Lac), the densities of the materials captured by the two components are assumed to be equal, and the calculated O'Connell effect is found to be almost equal to the observed effect. For three A-subtype W UMa systems (CN And, FG Hya and AU Ser), the two densities are assumed to be different, and are calculated separately. The calculated O'Connell effect turns out to agree better with the observed effect than that was formerly obtained.

Key words: binaries: close — star: W UMa — circumstellar matter

1 INTRODUCTION

Photometric observations of close binary stars showed that there is an obvious difference between the two maxima in the light curves of certain eclipsing systems. Wesselink and Milone (Milone 1968) called this phenomenon the O'Connell effect. The most intensive study of this phenomenon was done by O'Connell (1951), although Mergentaler's (1950) work on eight binary systems should be considered as an important precursor. O'Connell (1951) systematically examined the correlations between this effect and the system properties and concluded (1) that Δm (the magnitude difference maximum II-maximum I) was nearly always positive; (2) that Δm increases with increasing ellipticities of the stars and with increasing differences in the in

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size and density of the components; (3) that the smaller and denser the smaller star is, the bigger is the Δm, when the supergiant star is treated separately. Using modern high precision photoelectric data, Davidge & Milone (1984) re-examined and expanded on O'Connell's original findings. They found (1) that the strongest correlation is that involving the "color" of the asymmetry; (2) that the other strong correlations are those involving the size and ellipticity of the hotter component and the orbital period; (3) that the brighter maximum tending to be redder and (4) that in some systems, both the sign and amplitude of this effect change with time. Precise observations that have been carried out since the 1960s showed that the O'Connell effect generally exists in the short-period and/or late-type contact or near-contact binaries. The O'Connell effect is said to be positive or negative according as the first maximum (following the primary eclipse) is brighter or fainter than the second maximum (following the secondary eclipse).

Explanation of the O'Connell effect has been one of the celebrated difficult problems in the field of close binary systems. Before 1950 it was widely believed that the asymmetry had its origin in tidal and radiation enhancements during the periastron passage (Roberts 1906). O'Connell concluded that the asymmetries have nothing to do with the periastron passage and are the largest in systems in which the eccentricity was essentially zero. O'Connell pointed out that $\Delta m > 0$ was in agreement with Struve's (1948) twin stream model where the hotter stream, from the hotter, primary component, is seen unobstructed at maximum I. This gas stream hypothesis, however, cannot explain the color effect found by Davidge & Milone (1984), who suggested that H^- absorption may be a more appropriate mechanism. Binnendijk (1960) was the first to explain the asymmetry of the light curve of the binary AH Vir in terms of spot activities, and later on, many researchers went along this line (Bell et al. 1990; Linnell & Olson 1989). However, as pointed out by Maceroni & Van't Veer (1993), there is much uncertainty in the explanation by a spot activity model, as perfect fittings of some observed light curves can be obtained by many different spot models. Moreover, the scale of the O'Connell effect often is much larger than that of any spot activity (Yang & Liu 2002), and that if the spot model is used, the inferred spot area could be as large as 30% to 50% of the component's surface, which would be hard to understand. Shaw (1994) argued that the O'Connell effect of a near-contact binary is caused by the hot spot which formed when mass flows from one component to the other. The O'Connell effect in a contact binary with a common envelope, however, is hardly explained by the hot spot model of mass exchange. In a word, at present, the effect is not satisfactorily explained by any one of the models.

The present authors attempt to explain the O'Connell effect by the interaction of the components with the circumstellar material. The model is described in Section 2, a comparison of the model with the observational results is described in Section 3 and a discussion is presented in Section 4.

2 THE THEORETICAL MODEL

As there are various complicated interactions between the two components of a close binary, due to violent activities at the surfaces of the components, and to small disturbances in the size and shape of the Roche lobe, it is reasonable to consider that mass is constantly ejected from the surfaces of the two components, and form a circumstellar material envelope, with various states of motion. In fact, there is some evidence for the presence of circumstellar material in close binary systems. Northcott & Bakos (1967) were the first to suggest the presence of gaseous clouds in binary systems. Mclean (1982) also suggested the presence of circumstellar material near the primary component for the active binary ER Vul in order to account for the variations in the primary's spectral lines. Arevalo, Lazaro & Fuensalida (1988) also proposed that a high-temperature gas streams exist in some systems, based on their study of photometric variations. Shaw & Guinan (1990) observed the near-contact binary V1010 Oph with the IUE satellite and found Lyman-alpha emission at phases 0.25 and 0.75. They concluded that there is an additional source of Lyman-alpha emission around V1010 Oph. From JHKL observations of a number of eclipsing binaries displaying the O'Connell Effect, Milone (1976) concluded that we may expect that infrared excess, an indicator of the presence of circumstellar material, is a general property of close binary star systems.

We assume that the average velocity of part of the circumstellar material (mean density ρ) with respect to the mass center of the binary system is zero, and that the circumstellar material is captured by the components' forward hemispheres at their respective orbital speeds. We assume that all the kinetic energy of the material captured is turned into thermal energy, heating the atmosphere of the forward hemispheres, generating a temperature difference between the forward and back hemispheres of each component.

For the observer, the heated hemispheres of the primary and secondary components are alternately observed. Since the primary and secondary components are differently heated, the observed brightness is different between phase 0.25 and phase 0.75, i.e., we shall have the O'Connell effect.

In order to describe this model quantitatively, we assume the two components to be spheres synchronous rotation and set up a rotating rectangular coordinate system centered at its mass center of the system, with the x-axis along the line joining the two components (see Fig. 1). With the distances a and b as defined in the figure, the coordinates of the center of the primary are $[-(a+R_1), 0]$ and those of the secondary are $(b+R_2, 0)$, R_1 and R_2 being their respective radii in solar units.

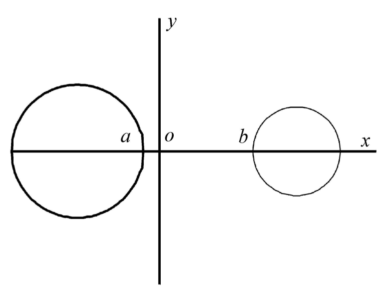

Fig. 1 A moving coordinate system.

According to the definition of the mass center of a binary system, we have

$$a = \frac{Aq - R_1(1+q)}{1+q}, \tag{1}$$

$$b = \frac{A - R_2(1+q)}{1+q}, \tag{2}$$

A being the distance between the two components in solar units and q is the mass ratio, $q = \frac{m_2}{m_1}$. The distribution of the circular orbital velocity (appropriate for close binaries) of the surface of a component is

$$V(x) = \frac{2\pi x}{p}, \tag{3}$$

where p is the orbital period of the binary in days. Let surface element $\mathrm{d}s = 2y\mathrm{d}x$; within one unit of time, the mass captured by $\mathrm{d}s$ is

$$\delta m = \frac{4\pi\rho yx\mathrm{d}x}{p}, \tag{4}$$

and its kinetic energy is

$$\mathrm{d}E = 0.5\delta mV^2(x) = \frac{8\pi^3\rho yx^3\mathrm{d}x}{p^3}, \tag{5}$$

(solar units throughout). For the stated spherical assumption, we have, for the primary,

$$y = \left(R_1^2 - \left(x - \frac{Aq}{1+q}\right)^2\right)^{1/2}, \tag{6}$$

and for the secondary,

$$y = \left(R_2^2 - \left(x - \frac{A}{1+q}\right)^2\right)^{1/2}. \tag{7}$$

The kinetic energy of the captured material is assumed to be completely turned into thermal energy, so the luminosity increases of the primary and secondary are

$$\Delta L_1 = \frac{8\pi^3\rho}{p^3}\int_a^{a+2R_1}\left(R_1^2 - \left(x - \frac{Aq}{1+q}\right)^2\right)^{1/2} x^3\mathrm{d}x, \tag{8}$$

$$\Delta L_2 = \frac{8\pi^3\rho}{p^3}\int_b^{b+2R_2}\left(R_2^2 - \left(x - \frac{A}{1+q}\right)^2\right)^{1/2} X^3\mathrm{d}x. \tag{9}$$

After integrations we have

$$\Delta L_1 = \frac{\pi^4 AqR_1^2\rho}{p^3(1+q)}\left(3R_1^2 + \frac{4A^2q^2}{(1+q)^2}\right), \tag{10}$$

$$\Delta L_2 = \frac{\pi^4 AR_2^2\rho}{p^3(1+q)}\left(3R_2^2 + \frac{4A^2}{(1+q)^2}\right). \tag{11}$$

The luminosities of the two components are,

$$L_1 = R_1^2T_1^4, \tag{12}$$

$$L_2 = R_2^2T_2^4. \tag{13}$$

Assuming counterclockwise rotation, the bolometric magnitude difference observed between the first maximum phase (the maximum after the primary eclipse) and the second maximum phase (the maximum after the secondary eclipse) should be

$$\Delta m = -2.5\log\frac{(L_1+L_2)+\Delta L_1}{(L_1+L_2)+\Delta L_2}. \tag{14}$$

As ΔL_1 is not equal to ΔL_2, so Δm is not zero, i.e., the O'Connell effect. It should be noted that this bolometric Δm differs from the usual O'Connell effect expressed in passband magnitudes because the bolometric corrections are different for the two components, even though the components of a contact system may have nearly the same effective temperature.

3 TESTING THE MODEL BY OBSERVATIONS

If the average density ρ of the circumstellar material is known, then the theoretical O'Connell effect, Δm, can be calculated and then compared with the observations. Unfortunately, so far we do not know how to determine ρ.

Now, in the research on late-type contact and near-contact binaries, there is the well-known problem of over-luminosity, meaning the observed luminosity of a binary is greater than the theoretical luminosity of the main-sequence star of the same mass.

If we now assume that the over-luminosity is equal to the sum $\Delta L_1 + \Delta L_2$ in our model, then we can use the two equations (10) and (11) to determine the density ρ and hence the theoretical O'Connell effect (14).

3.1 A simple explanation of the O'Connell effect in late-type and/or short-period binaries

One of the important observational facts is that the O'Connell effect can be observed in W UMa binaries and near-contact binaries. This fact can be explained well by our model. Kepler's Third Law may be written as

$$A^3 = 74.5 p^2 m_1 (1+q), \tag{15}$$

where A is the distance between the two components in solar radii, m_1 the mass of the primary in solar mass and p the orbital period in days. By definition, the relative radius of a component is

$$r_{1,2} = \frac{R_{1,2}}{A}. \tag{16}$$

Substituting Eqs. (10), (11), (12), (13), (15) and (16) into Eq. (14), we obtain

$$\Delta m = -2.5 \log \frac{B + 149\pi^4 q\rho[3r_1^2(1+q)^2 + 4q^2]}{B + 149\pi^4 (\frac{R_2}{R_1})^2 \rho[3r_2^2(1+q)^2 + 4]}, \tag{17}$$

where $B = \frac{T_1^4}{m_1} p(1+q)^2(1+\frac{L^2}{L^1})$.

Equation (17) shows that for late-type and/or short-period binaries we may easily have the O'Connell effect, because $\frac{T_1}{m_1}$ and p of a late-type and/or short-period binary are numerically small (see Table 1, where the data are cited from Allen (1973)).

Table 1 $\frac{T_1}{m_1}$ of Main Sequence Stars with Different Spectral Types

Sp.	O5	B0	B5	A0	A5	F0	F5	G0	G5	K0	K5	M0	M5
$\frac{T_1}{m_1}$	56.81	30.56	7.89	2.62	2.21	1.56	1.28	1.06	0.88	0.56	0.37	0.28	0.26

An example now follows. Assume that the primary is a main sequence star, the orbital period of the binary is $p = 0.5\,\mathrm{d}$, the mass ratio $q = 0.4$, the luminosity ratio $\frac{L_2}{L_1} = 0.03$, the radius ratio $\frac{R_2}{R_1} = 0.5$, $r_1 = 0.4$, $r_2 = 0.2$ and $\rho_1 = 3 \times 10^{-12}\,\mathrm{g\ cm^{-3}}$, and assuming the theoretical values of the effective surface temperatures and masses of the main sequence stars for given spectral types, we calculate Δm by Eq. (17). The results are shown in Figure 2. If the spectral type of the binary is G5V, then $\frac{T_1^4}{m_1} = 0.888$, for the above assumed values of the mass ratio, radius ratio and relative radius of the components. Figure 3 shows Δm for different orbital periods.

The observational fact that the O'Connell effect is produced in late-type and/or short-period binaries is naturally explained by Figs. 2 and 3 obtained from our model. The two figures show that the O'Connell effect is easily observed in binaries with orbital periods less than one day and spectral types later than F0.

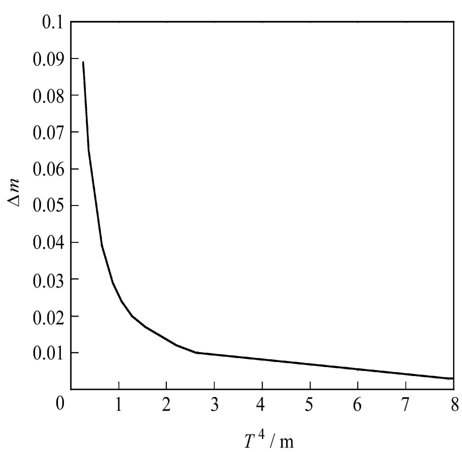

Fig. 2 O'Connell effect as a function of the mass and temperature of the primary.

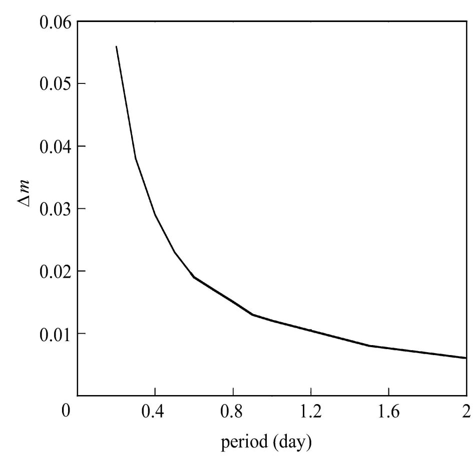

Fig. 3 O'Connell effect as a function of the orbital period.

3.2 Theoretical O'Connell effect for three W-subtype W UMa binaries

YY Eri is a W-subtype W UMa binary with spectral type G5V and orbital period 0.3215 d. Batten et al. (1989) gave the spectroscopic orbital solutions, and Maceroni et al. (1994) and Yang & Liu (1999) carried out a photoelectric photometry and analysis. In the V band, $\Delta m = -0.04^{\rm m}$. According to the relevant parameters given by Maceroni et al. (1996), $m_1 = 1.02\,M_\odot$, $m_2 = 0.44\,M_\odot$ and the sum of the luminosities of the two components $L_1 + L_2 = 1.12\,L_\odot$ based on the mass- luminosity relation of main sequence stars, while the observed sum of luminosities is $1.20\,L_\odot$, i.e., the observed is greater than the theoretical by $0.08\,L_\odot$. According to our model, this over-luminosity can be understood as the result interaction of the circumstellar material with the components. From Eqs. (10) and (11), one may obtain $\rho = 3.6 \times 10^{-12}\,{\rm g\ cm^{-3}}$, and from Eq.(17) one then obtains $\Delta m = -0.07$ bolometric. it is close to the practically measured value, –0.04 in V.

BX Peg is a W-subtype W UMa binary with spectral type G4V and orbital period 0.2804 d. A photoelectric photometry and analysis was published by Kaluzny(1984). According to the relevant parameters given by Maceroni et al.(1996) and our model, one may obtain $\rho = 2.89 \times 10^{-12}\,{\rm g\ cm^{-3}}$ and hence $\Delta m = -0.04$ bolometric, which is close to the observed –0.02

in V.

SW Lac also is a W-subtype W UMa binary with spectral G8V and orbital period 0.3207 d. The results of a photoelectric photometry and spectroscopic study were given by Zhai & Lu (1989). According the relevant parameters from Maceroni et al. (1996) and from the model calculation, we find $\rho = 2.52 \times 10^{-12}$ g cm^{-3} and $\Delta m = 0.02$ bolometric, also close to the measured 0.04 in V.

3.3 Comparison of theory with the observed O'Connell effect in three A-subtype W UMa binaries

For CN And, FG Hya and AU Ser, we assume that the density of the circumstellar material captured by the primary is different from that by the secondary, the two densities are calculated separately from Eqs. (10) and (11). Then, using the over-luminosity for each of the two components, we obtain the theoretical O'Connell effect from Eq. (17) and compare it with the observed value.

CN And is an A-subtype W UMa binary, with spectral type F8 and orbital period 0.4628 d. Results of a photometry were given by Rafert et al. (1985). According to the relevant parameters from Maceroni et al. (1996), the over-luminosity of the primary is $\Delta L_1 = 0.409\, L_\odot$ and that of the secondary, $\Delta L_2 = 0.372\, L_\odot$. From these we derive teh two densities ρ_1 and ρ_2: $\rho_1 = 3.79 \times 10^{-11}$ g cm^{-3}; $\rho_2 = 1.40 \times 10^{-11}$ g cm^{-3}. From Eq.(17) we then find the theoretical O'Connell effect $\Delta m = -0.032$ bolometric, which almost coincides with the observed value –0.04 magnitude in the B band.

FG Hya is an A-subtype W UMa binary, with spectral type G0 and orbital period 0.3278 d. Photoelectric photometric observations and analyses for this system were given by Twigg et al. (1979) and Yang et al. (1990). According to the relevant parameters from Maceroni et al. (1996), the over-luminosity of the primary is $\Delta L_1 = 0.256\, L_\odot$ and that of the secondary is $\Delta L_2 = 0.289\, L_\odot$. Proceeding as before, we find $\rho_1 = 6.86 \times 10^{-11}$ g cm^{-3}, $\rho_2 = 2.16 \times 10^{-11}$ g cm^{-3}, $\Delta m = 0.026$ bolometric; the last is consistent with the observed value of 0.02 in B.

AU Ser is another A-subtype W UMa binary, with spectral type G5 and orbital period 0.3865 d. A photoelectric photometry and a solution of the binary were given by Kaluzny et al.(1986), and spectroscopic observations and analysis are from Hrivnak (1993). The mass ratios obtained from the photometric and spectroscopic observations are respectively 0.800 and 0.710, and we adopt $q = 0.75$ in the present work. According to the relevant parameters from Maceroni et al. (1996), the over-luminosity of the primary is $\Delta L_1 = 0.120\, L_\odot$ and that of the secondary is $\Delta L_2 = 0.090\, L_\odot$. Pan indicator of the presence of circumstellar material. Proceeding as before, we obtain $\rho_1 = 8.90 \times 10^{-12}$ g cm^{-3}, $\rho_2 = 4.32 \times 10^{-12}$ g cm^{-3} and $\Delta m = -0.042$ bolometric. The last is in accordance with the observed value of –0.05 in B.

The calculated O'Connell effect refers to the bolometric magnitude while the observed effect, to the B magnitude. However, we may expect the values in the two cases to be nearly equal, because the temperature is almost the same at the two orbital phases that define the O'Connell effect.

4 DISCUSSION

The theoretical model for explaining the O'Connell effect in the present paper proceeds from the assumption that the components of a binary capture the circumstellar material at rates corresponding to their orbital velocities.

(1) The observed fact that only late-type and/or short-period binaries can have the O'Connell effect, can be quite naturally explained by the present model. Since no restriction is imposed on the spectral type of the components or the orbital period of the systems, the model should be applicable to all binaries. However, the results inferred from the model show that only late-type and/or short-period binaries can easily produce obvious O'Connell effects.

(2) The observed O'Connell effects in six binaries are successfully explained. We examined three W-subtype W UMa binaries (YY Eri, BX Peg and SW Lac), and assumed that the materials captured by the primary and secondary have the same density, which was calculated from the "over-luminosities". The calculated O'Connell effect agrees well with the observed effect in all three cases. For the three A-subtype W UMa binaries (CN And, FG Hya and AU Ser), we assumed that the densities of the circumstellar material captured by the two components are different; the two densities were separately calculated from the individual over-luminosities. The calculated O'Connell effect in these three cases agreed better with the observed effect than that was formerly obtained.

Two principal assumptions are made in the present model for the convenience of calculation and because of a lack of understanding of the state of the circumstellar material. The first assumption, made for the convenience, is that the two components are spheres, The actual shape of binary components usually deviates from a sphere because of their gravitational interaction, of their fast rotation and so on. Strictly speaking, the shape of the components as defined in the Roche geometry should be used. However, the spherical approximation cannot produce order of magnitude errors, and since the observed O'Connell effect is expressed by a magnitude difference, any error caused by the spherical approximation should not have any obvious effect. The second assumption is in regard to the state of motion of the circumstellar material. For lack of available evidence it looks as though our assumption can only be tested by future observations. Considering the complexity and variability of the source of the circumstellar material, a natural inference of the present model is that the O'Connell effect should be variable, and this accords with the observations that the O'Connell effect is certainly variable and apparently varies at random.

Inasmuch as the density and dynamic state of the circumstellar material are approximately given, the specific value of the O'Connell effect for a given binary obtained by the calculation is also only approximate. However, the consistent agreement between our calculated theoretical values with the observed values suggests that the present model is probably correct in principle. On the other hand, if our model is correct, then the density of the circumstellar material and the variation of the density should be inferable from the measurement of the O'Connell effect. Therefore, this may also be a way to understand some of the characteristics of the circumstellar material of the binary systems. According to the results obtained from the examples, the density of the circumstellar material in these systems is consistently greater than 10^{-12} g cm^{-3}, which is enough to produce some spectroscopically observable effect. Although profiles of spectroscopic lines of contact and near-contact binaries are distorted by complex interaction between the two components, from spectra with high signal-noise ratio and high resolution one should be able to obtain some evidence of the circumstellar material. Furthermore, the profiles of the spectroscopic lines at the two light maximum phases may be different, in a similar manner as the O'Connell effect in the photometric light curve.

The present model is only a preliminary attempt to explain the O'Connell effect in the light curves of eclipsing binaries. To verify the model, the relation between circumstellar material and the O'Connell effect should be investigated through further observations. In addition, a simulation of the dynamical state of circumstellar material of eclipsing binaries should be carried out.

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References

Allen C. W., 1973, Astrophysical Quantities, p.251
Arevalo M. J., Lazaro C., Fuensalida J. J., 1988, AJ, 96, 1061
Batten A. H., Fletcher J. M., McCarthy D. G., 1989, Publ. D. A. O., XVII
Bell S. A., Rangier P. P., Hilditch R. W., 1990, MNRAS, 247, 632
Kaluzny J., 1984, Acta Astron., 34, 217
Binnendijk L., 1960, AJ, 65, 385
Davidge T. J., Milone E. F., 1984, ApJS, 55, 571
Hall J. C., Ramsey L. W., 1992, AJ, 104, 1942
Hrivnak B. J., 1993, in New Frontiers in Binary Star research, K.-C. Leung and I. S. Nha, eds, PASPC 38, p.269
Kaluzny J., 1984, Acta Astron., 34, 217
Kaluzny J., 1986, Acta Astron., 36, 113
Linnell A. P., Olson E. C., 1989, ApJ, 343, 909
Maceroni C., van't Veer F., 1993, A&A, 277, 515
Maceroni C., Vilhu O., van't Veer F., 1994, A&A, 288, 529
Maceroni C., van't Veer F., 1996, A&A, 311, 523
McLean B. J., 1982, MNRAS, 201, 421
Mergentaler J., 1950, Wroclaw Contr., no. 4. p.1
Milone E. F., 1968, AJ, 73, 708
Milone E. F., 1976, In: B. Szeidl, ed., IAU Coll., 29, Proceeding, Multile Periodic Variable Stars, p.321
Northcott R. J., Bakos G. A., 1967, AJ, 72, 89
O'Connell D. J. K., 1951, Pub. Riverview College Obs., 2, 85
Rafert J. B., Markworth N. L., Michaels E. J., PASP, 97, 310
Roberts A. W., 1906, MNRAS, 66, 123
Shaw J. S., 1994, Mem. S. A. It., 65, 1
Shaw J. S., Guinan E. F., Garas C. J., 1990, BAAS, 22, 1296
Struve O., 1948, PASP, 60, 160
Twigg L. W., 1979, MNRAS, 189, 907
Yang Y., Liu Q., 1999, A&AS, 136, 139
Yang Y., Liu Q., 2002, Chin. J. Astron. Astrophys. (ChJAA), 2, 369
Yang Y., Liu Q., Zhang Y., Wang B., 1991, Acta Astron. Sin., 32, 326
Zhai D., Lu W., 1989, Chin. Astron. Astrophys., 9, 208