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The Historical Re-Brightening and Distance Recheck of SN 1006 *

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Abstract We presume the re-brightening of SN 1006 in AD 1016 as recorded in the ancient Chinese literature to be true and the re-brightening was caused by the encounter either of photons or the shock wave from the SN outburst with the circumstellar thin envelope materials. Based on these considerations, and combining the observational results on the optical proper motion of the N-W limb and the radio observations of the other parts of the supernova remnant G327.6+14.5, we re-determine the distance to SN 1006. For the photon-encounter model, the average radius of the envelope material would be 10 ly; and for the shock wave-encounter model, the radius would be about 1 ly. We then set up four equations to solve for the distance of the SN, the initial shock speed, the expansion index for two different parts of the supernova remnant, and the real original radius of the thin envelope nebula. It is indicated that only the case of photon-encounter will lead to a reasonable result. We derived a distance of 5074 ly (1.56 kpc), an original shock expansion velocity of $0.071c$, an expansion index of 0.72 for the N-W limb of the SNR, and 0.76 for the other parts . We deem that the SNR evolution is still in the stage of reverse shock.

Key words: supernova: supernova remnant — SN 1006 distance — Zhou-Bo Star — planetary nebula

1 INTRODUCTION

SN 1006 was one of the brightest supernovae (SNe) humans have observed until now. The peak apparent magnitude of SN 1006 has been estimated as –5.5 to –10.0 by different authors (Stephenson, Clark & Crawford 1977; Bo et al. 1987; Stephenson & Green 2002). The distance of G327.6+14.5 has been determined to be from 1 kpc to 2.8 kpc (Schweizer & Middleditch 1980; Vartanian, Lum & Ku 1985; Hamilton, Sarazin & Szymkowiak 1986; Hamilton & Fesen 1988; Green 1988; Strom 1988; Fesen et al. 1988; Smith et al. 1991; Wu et al. 1993; Laming et al. 1996; Winkler et al. 2003). Most researchers have chosen G327.6+14.5 (= PKS 1459–41) as the resulting supernova remnant (SNR), as first suggested by Gardner & Milne (1965). However, some authors have argued that PKS 1527–42 (Bo et al. 1987) or the Lupus Loop (Stephenson, Clark & Crawford 1977) might be the SNR. All those objects have very large angular size on the sky, e.g., for G327.6+14.5 is about $30'$ in diameter. Hence the distance of the SN cannot be very large unless none of them are the remnant of so young a supernova. For example, the diameter of the remnant of SN 1054, with a similar age, is only about $6'$ or one-fifth of that of G327.6+14.6. Moffett et al. (1993) and Winkler et al. (2003) presented observational results of G327.6+14.5. On the other hand, Wang (1979) reported a document in an ancient Chinese historical book as showing that in AD 1016, SN 1006 (the Zhou-Bo Star) once "re-appeared". We deem that the event should be caused by the encounter either of the photons or the shock wave from the SN outburst with the materials of the thin circumstellar envelope of the SN progenitor. Taking the modern observational results and the quoted "re-appearance" event of SN 1006 in AD 1016, we suppose that the progenitor white dwarf of SN 1006 had a thin enveloping planetary nebula of 10 ly in radius. We derived a new distance of SN 1006 of 5074 ly or 1.56 kpc. This value is within the range derived by some modern observations (e.g., Laming et al. 1996).

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2 THE CHINESE HISTORICAL RECORD ON THE RE-BRIGHTENING OF SN 1006

In the Chinese historical book "*A Continuation of Zi Zhi Tong Jian*" (edited by Li Dao, a historian of the Southern Song Dynasty (AD 1127–1279)), there are two entries on a "Zhou-Bo Star". The first is in volume 26: "In the fifth month of the Third Year of Jing-De Reign-period (May 30, AD 1006), on the first day of the lunar month, (the Yin-Ren day), Si-Tian (the Astronomer Royal) reported: a Zhou-Bo Star appeared". It has an added footnote: "The event on the Geng-Chen day of the Fourth month in the Ninth year of Xiang-Fu (May 16, AD 1016) should be referred to". The second recorded item is in volume 32: "On the Geng-Chen day of the Fourth month of the Ninth Year of Da-Zhong Xiang-Fu (May 16, AD 1016), Si-Tian said: the Zhou-Bo Star reappeared". It also has a footnote: "The event on the first day of the lunar month in the Fifth month in the Third year of Jing-De (May 30, AD 1006) should be referred to".

These two footnotes show that the writer has firmly made a connection of the two events that took place on May 30, AD 1006 and on May 16, AD 1016, respectively. This indicates that he must confidently believe that the two events occurred on the same celestial body, namely, the Zhou-Bo Star that first appeared in 1006. We know that in the Northern Song Dynasty (AD 960–1127) astronomical measurements were made with quite high accuracy, and that the period between the Third Year of Jing-De and the Ninth Year of Da-Zhong Xiang-Fu the society of China was generally peaceful and flourishing, and that in the period China has never used the AD annals. Therefore, we treat the judgment made by the royal astronomers to be reliable and not a mistake. Wang (1979) noticed these two footnotes and argued that the remnant of SN 1006 once recurred as a re-brightening in AD 1016.

As a type Ia supernova, SN 1006 might be caused by an accreting white dwarf in a binary system. After the SN burst almost nothing survived in the center except the other companion in the binary system. Hence it is almost impossible that SN 1006 really "re-bursted" 10 years after its initial outburst. So, we suspect that the event in AD 1016 was a brightening of the circumstellar material. According to the evolutionary theory of SN Ia, the progenitor of SN 1006 (the binary system) must have had a thin, enveloping circumstellar nebula (with radius r, say) produced very early in the red giant stage (slow wind) and the white dwarf stage (fast wind). This thin circumstellar envelope is the disappearing planetary nebula of the progenitor white dwarf. The space between this envelope and the white dwarf is almost empty due to the accretion for the SN outburst.

3 A GOOD COINCIDENCE OF THE RE-BRIGHTENING OF SN 1006 WITH A MODERN ANALYTICAL RESULT

Badenes & Bravo (2001) examined the effect of pre-supernova evolution imprinted on the SNR, and suggested four wind models for SN Ia. They showed that their Model A gives results more consistent with several features of SNR 1006, but none of the four models fitted very well with an SN Ia. However, we can find that in their model B (see figure 2 of Badenes & Bravo 2001) the distribution profile of ambient circumstellar material density has a sharp peak of about 100 particles per cubic centimeter at a radius r about 10 ly and almost 0 particles at all other parts. Therefore, the analytical result of a high density shell with a radius of 10 ly would be a good coincidence with the SN 1006 re-brightening in AD 1016, if there was in fact a circumstellar nebula brightening at radius of 10 ly.

On the other hand, from the observations of SN 1987A in the period 1988 to 2000, the ring-shaped nebula can be seen as bright by scattering or reflecting the photons of the SN outburst (Crotts, Kunkel & McCarthy 1989; Sugerman et al. 2005) or be excited by shock wave encounter (Maran et al. 2001). So the re-brightening of SN 1006 in AD 1016 could possibly occur by one of the two causes: the photons or the shock wave of the SN outburst.

4 CALCULATIONS OF THE DISTANCE

Let D be the distance of G327.6+14.6 in ly. Assuming that the SN had a thin circumstellar envelope nebular that re-brightened in 1016, we obtain that the original angular size of the circumstellar nebula of SN 1006 is $\tan^{-1}(10\,\mathrm{ly}/D)$ for the photon encounter model, or $\tan^{-1}(10\,\mathrm{y} \times v/D)$ for the shock wave encounter model, where v is the velocity of shock wave. For an SN Ia, the original shock wave velocity v should be from 10 000 to 30 000 km s^{-1} or 0.033 to 0.1 times of the light speed c. After encountering the envelope, the shock wave velocity would be slowed down. Winkler et al. (2003) have given a law of decrease, $\theta \propto t^m$, where θ is the angular radius of the SNR at time t years after the SN outburst in units of arcsec,

$m = d\,(\log\theta)/d(\log t) = (d\theta/dt)/\,(\theta/t)$ is the expansion index. We can write it as

$$\theta = At^m, \tag{1}$$

where A is a constant.

The proper motion of the limb of the SNR is

$$\mu = d\theta/dt = Amt^{m-1}, \tag{2}$$

in units of arcsec per year. Then we have $m = \mu t/At^{m-1+1} = \mu t/\theta$. Winkler et al. (2003) presented that at t = 992, for most parts of the SNR, θ is equal to 900 arcsec, but for the N-W limb, θ is equal to 816 arcsec. In the following we analyze the two cases, the photon and the shock wave mechanisms, separately.

4.1 The Case of Photons Encountering the Circumstellar Materials

We first consider the case that photons from the SN outburst encountered the circumstellar materials resulting in the re-brightening. As we mentioned above, the radius of the thin enveloping nebula, r, is equal to 10 ly, so T_1 = 10 ly/v, in yr, is the time for the debris produced from the SN outburst to reach the enveloping nebula, and $T_2 = T - T_1$, where T is the time (in yr, counted from the original outburst of the SN) to produce the observed proper motion μ of the SNR limb. For most parts of the nebula T= 985 yr and μ= 0.438 arcsec (Moffett et al. 1993), but for the N-W limb $T = 992$ yr and μ = 0.279 arcsec (Winkler et al. 2003).

Considering the white dwarf's strong radiation pressure and the accretion, we can be sure that before T_1, m is equal to 1 and the angular expansion rate is 206265 (v/D) arcsec per year, until an angular size of 2062650/D arcsec is attained. Once T_1 is passed, the angular expansion rate began to decrease.

At $T = 985$ yr after the SN outburst, m = 0.48 arcsec, μ = 0.438 arcsec, then we obtain $\theta = \mu t/m =$ 900 arcsec, and then

$$A(985 - 10/v)^m = 900 - 2062650/D. \tag{3}$$

If we take m as a constant equivalent value, we have

$$Am(985 - 10/v)^{m-1} = 0.438. \tag{4}$$

Let $m_{(\mathrm{N-W})}$ and $A_{(\mathrm{N-W})}$ be the expansion index and the constant respectively for the N-W limb:

$$A_{(\mathrm{N-W})}(992 - 10/v)^{m(\mathrm{N-W})} = 816 - 2062650/D. \tag{5}$$

If we also take $m_{(\mathrm{N-W})}$ as the constant equivalent value, we have

$$A_{(\mathrm{N-W})}m_{(\mathrm{N-W})}(992 - 10/v)^{m(\mathrm{N-W})-1} = 0.279. \tag{6}$$

From Equation (1), we find that $A = A_{(\mathrm{N-W})}$=206265v/D is the initial angular expansion speed. So we have obtained four equations with four unknowns, v, D, m, and $m_{(\mathrm{N-W})}$. Solving these equations we obtain all the four unknowns. The final solutions are: $D = 5074$ ly, $v = 0.071\,c$, $m = 0.76$ and $m_{(\mathrm{N-W})} = 0.72$.

Therefore, for G327.6+14.6, the distance is 5074 ly and its evolution is still at the early stage number 2. This is consistent with the fact that the age of SN 1006 was no more than 1000 years during the observations.

4.2 The Case of Shock Wave Encountering the Circumstellar Materials

We consider the case of shock wave encountering the circumstellar materials resulting in the re-brightening. As $T_1 = 10$ yr and $T = 985$ yr after the SN outburst, we have

$$A(985 - 10)^m = 900 - 2062650(v/D). \tag{7}$$

If we take m as a constant equivalent value, we then have

$$Am(985 - 10)^{m-1} = 0.438. \tag{8}$$

For the N-W limb,

$$A_{(\mathrm{N-W})}(992 - 10)^{m(\mathrm{N-W})} = 816 - 2062650(v/D). \tag{9}$$

We also take $m_{(\mathrm{N-W})}$ as the constant equivalent value, we have

$$A_{(\mathrm{N-W})}m_{(\mathrm{N-W})}(992-10)^{m(\mathrm{N-W})-1}=0.279. \tag{10}$$

From Equation (1), we can understand that A and $A_{(\mathrm{N-W})}$ equal to 206265 (v_1/D) and 206265 (v_2/D) are the initial angular expansion speed for most parts and the N-W limb, respectively. So we have obtained four equations with four unknowns, i.e., v, D, m, and $m_{(\mathrm{N-W})}$. From Equations (7) and (8), we have $0.438\times 975/m = 900$ – 2062650 (v/D), or $427.05/m = 900 - 10A = A975^m$. Then $m = 0.569$, and

$$A = 206265\,(v/D) = 14.9494. \tag{11}$$

From Equations (9) and (10), for the N-W limb we have 0.279 × 982 / $m_{(\mathrm{N-W})}$ = 816 – 2062650 (v/D), or 273.978 / $m_{(\mathrm{N-W})}$ = 816 – 10A = A $_{(\mathrm{N-W})}$982$^{m(\mathrm{N-W})}$, and 816 $m_{(\mathrm{N-W})}$ = 273.978 + 2.79 × 982$^{m(\mathrm{N-W})-1}$. So, we obtain $m_{(\mathrm{N-W})}$ = 0.469, and

$$A_{(\mathrm{N-W})} = 206265\,(v/D) = 23.1429. \tag{12}$$

From Equations (11) and (12), we obtain a different initial shock wave speed and the speed of the N-W limb is larger than that of the other parts. For this $A_{(\mathrm{N-W})}$, if $D \geq 1000$ ly, v will be larger than 0.11c, and if D = 5000 ly, v larger than 0.55c. Therefore, we may conclude that only the case that the re-brightening resulted from photon excitation and/or scattering and/or reflecting is reasonable, unless that the distance D is smaller than 1000 ly, which is definiely inconsistent with the observational results and so hardly believable.

5 CONCLUSIONS

Considering the re-brightening of SN 1006 in AD 1016 recorded in the ancient Chinese literature and some modern observational results, we re-determined the distance of SN 1006 and the result is 5074 ly or 1.56 kpc. We prove that the cause of the re-brightening of the SNR in AD 1016 was photons encountering the thin envelope circumstellar materials left over by the planetary nebula of the progenitor white dwarf of the SN. It is noted that our results are based on the historical record and hopefully will be examined by more observational data in the future.

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References

Badenes C., Bravo E., 2001, ApJ, 556, L41
Bo Sh. R., Wang, J. M., Liu, J. Y., 1987, in: J. C. Liu, ed., New Studies on the History of Chinese Astronomy, Taibei, Mingwen Publishing House, p.288
Crotts A. P. S., Kunkel W. E., McCarthy P. J., 1989, ApJ, 347, L61
Fesen R. A., Wu C. C., Leventhal M., Hamilton A. J. S., 1988, ApJ, 327, 164
Gardner F. F., Milne D. K., 1965, AJ, 70, 754
Green D. A., 1988, Ap&SS, 148, 3
Hamilton A. J. S., Sarazin C. L., Szymkowiak A. E., 1986, ApJ, 300, 698
Hamilton A. J. S., Fesen R. A., 1988, ApJ, 327, 178
Laming J. M., Raymond J. C., McLaughlin B. M., Blair W. P., 1996, ApJ, 472, 267
Maran S. P., Sonneborn G., Pun Chun S. J., Lundqvist P., Iping R. C., Gull T. R., 2000, ApJ, 545, 390
Moffett D. A., Goss W. M., Reynolds S. P., 1993, AJ, 106, 1566
Schweizer F., Middleditch J.,1980, ApJ, 241, 1039
Smith R. C., Kirshner R. P., Blair W. P., Winkler P. F., 1991, ApJ, 375, 652
Stephenson F. R., Clark D. H., Crawford D. F., 1977, MNRAS, 180, 567
Stephenson F. R., Green D. A., 2002, in: F. R. Stephenson, D. A. Green, ed., Historical Supernovae and Their Remnants, Cambridge University Press, p.171
Strom R. G., 1988, MNRAS, 230, 331
Sugerman B. E. K., Crotts A. P. S., Kunkel W. E., Heathcote S. R., Lawrence S. S., 2005, ApJS, 159, 60
Vartanian M. H., Lum K. S. K., Ku W. H.-M., 1985, ApJ, 288, L5
Wang J. M., 1979, Publication of the Beijing Astronomical Observatory, 1, 69
Winkler P. F., Gupta G., Long K. S., 2003, ApJ, 585, 324
Wu C. C., Crenshaw D. M., Fesen R. A., Hamilton A. J. S., Sarazen C. L., 1993, ApJ, 416, 247