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A1_10 The Star of Bethlehem: A Violent Explosion

Y. Davis, N. Drewes, T. Lomax, S. Norman

Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH

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Abstract

In this paper, we examine the feasibility and implications of the theory that the Star of Bethlehem was a supernova in the Andromeda Galaxy. Using the limiting magnitude of the human eye and Type Ia supernova light curves, we found the absolute maximum magnitude of the supernova to be −20.6. In addition, inferring its energy budget for the supernova remnant expansion from its magnitude, we conclude that these remnants with a size of 0.3 pc could be resolved by the Very Large Telescope today.

Introduction

In the Christmas story, the Star of Bethlehem guides the three wise men to Jesus. In ancient times, wise man, or 'magi', was also used to refer to astronomers. Therefore, it is reasonable to assume the Star of Bethlehem was a time-limited astronomical event, such as a supernova (the violent explosion of a star). Here we examine the theory proposed by Frank Tipler, that the star was a Type Ia supernova in the Andromeda Galaxy [1]. We aim to find its maximum absolute magnitude using Type Ia light curves and accordingly estimate its energy budget and determine whether its remnants could be resolved today.

Supernova Magnitude

Since around Jesus' birth no telescopes were available, any supernova must have crossed the threshold apparent magnitude for human-eye detection, which is 6.5 [2]. For an object in the Andromeda Galaxy at a distance of 750 kpc, this translates to an absolute magnitude of $M_0 = -17.9$ [3]. As there is 13 days between Christmas Eve and Epiphany, we can assume that over 15 days the supernova declined from its maximum absolute magnitude M_{max} to M_0, covering a total magnitude difference of $M_0 - M_{max}$. Type Ia supernova have very typical light curves, and the rate of their descent Δm_{15} from M_{max} within 15 days is well-defined through the luminosity-decline rate relation. Here, we will use the first linear definition of this relation: $M_{max} = a + b\Delta m_{15}$ [4]. In addition, the definition of a rate gives Δm_{15} as $(M_0 - M_{max})/15$ days. Solving both these equations for M_{max} gives

$$M_{max} = (bM_0 + 15a)/(15 + b). \tag{1}$$

Working in the visual magnitudes, $a = -21.0$ and $b = 2.0$ [4]. Therefore, Eq. 1 gives the maximum absolute magnitude of the supernova as −20.6. In fact, this is typical for Type Ia supernova, which shows that it is practical for the Star of Bethlehem to have been a supernova.

Supernova Remnants

After supernovas explode, they spread their material through space as they expand. As shown by our observations of the Crab Nebula – the remnant of a supernova that occurred in 1054 – these remnants can be observed for a long time following the event. Considering the maximum absolute magnitude of the event and its connected energy budget, we can evaluate how far the supernova spread. The luminosity of the supernova can be found using its absolute magnitude relation to the Sun, or solving

$$M = M_{sun} - 2.5 \log_{10}(L/L_{\odot}) \tag{2}$$

for L, where $M_{sun} = 4.74$ is the Sun's absolute magnitude, $L_{\odot} = 3.8 \times 10^{26}$ W is its luminosity, and M is the absolute magnitude of the supernova [5]. As we are considering the time of 15 days where the supernova is visible, we can take its average absolute magnitude as -19.3 to find its average luminosity. Solving Eq. 2 using the aforementioned values gives the average luminosity as 1.5×10^{36} W. Over 15 days, this is a total energy budget of 2.0×10^{42} J.

The first phase of supernova expansion is called the free expansion phase, where the expelled matter from the supernova moves relatively unimpeded through the interstellar medium [5]. These typically last thousands of years, so here we assume the supernova remnant to still be in this phase. The radius of the supernova remnant R_S is then simply

$$R_S = v_e t, \tag{3}$$

where t is the time since the explosion and v_e is the velocity of the ejected material. This velocity can be found from the kinetic energy of this material, which we assume to be equal to the energy budget as calculated above. Assuming the mass of the ejected material to be $10\,\mathrm{M}_{\odot}$, this gives a velocity of $140\,\mathrm{km\,s^{-1}}$ [5]. Using Eq. 3 over a time of 2000 years, the size of the supernova remnant would be about 8.8×10^{15} m, or 0.29 pc today.

Next, we investigate whether we would be able to resolve an object of that size in the Andromeda Galaxy today. The angular resolution θ of a telescope is given by $\theta = 1.22\lambda/D$, where D is the diameter of the telescope and λ is the wavelength in which observations are taken. For the Very Large Telescope in Chile with $D = 8.1$ m and observing in the optical at $\lambda = 500$ nm, the angular resolution is 7.5×10^{-8} rad [6]. Since the supernova remnant is very far away, its angular size can be approximated by dividing its actual size by the distance to the Andromeda Galaxy, which gives 3.7×10^{-7} rad. As this is larger than the angular resolution, it will be resolved and we could observe it today.

Conclusion

A supernova is very attractive explanation for the Star of Bethlehem as its occurrence is short and it is very bright. Here we have shown that assuming it occurred in the Andromeda Galaxy, it is also a physically reasonable explanation, with a maximum absolute magnitude of -20.6, typical of Type Ia supernova. In addition, we are theoretically able to resolve its remnants today. However, since the Andromeda galaxy is very bright on its own, it will be difficult to detect. Nevertheless, any supernova event is reasonable explanation for the Star of Bethlehem.

References

[1] F. J. Tipler, Observatory **125** (2005).

[2] `https://astronomy.swin.edu.au/cosmos/L/Limiting+Magnitude` [Accessed 2 December 2020].

[3] `https://astronomy.swin.edu.au/cosmos/A/Andromeda+galaxy` [Accessed 2 December 2020].

[4] M. M. Phillips, Astrophys. J. Lett. **413**, L105 (1993).

[5] B. W. Carroll and D. A. Ostlie, *An Introduction to Modern Astrophysics* (Cambridge University Press, Cambridge, 2017).

[6] `https://www.eso.org/public/teles-instr/paranal-observatory/vlt/` [Accessed 2 December 2020].