THE DYNAMIC EVOLUTION OF THE KEPLER SUPERNOVA REMNANT

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Abstract. Two supernovae exploding events were observed visually from the same position, the north of Tian-Jiang in Wei-Suei (the north of 42 θ Ophiuchi), in 1604 and 1664, respectively, and were recorded in the ancient astronomical literatures of China and Korea. However, in recent years only one supernova remnant (SNR) has been identified in this position using advanced optical, radio and X-ray techniques. Some observed information for the Kepler SNR, including its non-spherically symmetric emission property with brighter north but darker south, have been shown. We conjecture that a supernova outburst in 1664 was excited by the 1604 supernova explosion at a distance of about 0.5 parsecs. The present SNR is formed from the summation of these two explosions. The dynamical evolution of the Kepler SNR is studied by means of a time-dependent, hydrodynamic code in the present paper. The density, velocity, temperature, and X-ray emission distribution of the SNR are shown, being the results of dynamic evolution for 380 years following the explosion of the supernova in 1604. Compared with present radio and X-ray observations, these numerical results may reasonably explain the observational features.

1. Introduction

Supernova 1604 – called the Kepler supernova – is one of three supernovae which exploded in the Galaxy during the last 500 years. It has been recorded both in Chinese 'Ming Shi' (the historical records of the Ming Dynasty) and in Korean 'Lichao Shilu' (the historical records of the Li Dynasty) (Xi and Bo, 1965). In Europe, this event was observed in more detail by Kepler, the German astronomer. It is well known that the Kepler supernova is of type I. According to 'Lichao Shilu', in 1664 another supernova outburst event was seen near the same position, to the north of 42 θ Ophiuchi, where the Kepler supernova had appeared in 1604 (Xi and Bo, 1965). However, only one SNR has been detected by modern astronomical instruments in this direction. At first, optical studies were made in some detail by Baade (1943), who indicated that the structure of the remnant is not uniform and has bright filament patches. Gull found some optical filaments having velocities only about 200 km s^{-1} in the radio shell (Gull, 1975; van den Bergh *et al.*, 1973). In addition, Minkowski noted that the radial velocity of an optical filament near the projected centre of the remnant is about -275 km s^{-1} (Minkowski, 1968). A high-resolution radio observation for the Kepler SNR was made by Gull (1975). White and Long (1983) reported X-ray results using the instruments on board the *Einstein* Observatory. The positions of the radio and the X-ray image of the Kepler SNR are almost the same, in the central direction of our Galaxy, $\alpha_{1950} = 17^h27^m43^s$, $\delta_{1950} = -21°27'$. The remnant is nearly circular in shape with a diameter of 3$'$. The estimated distance of the Kepler SNR is 3.2–12 kpc from the Sun, and 5 kpc is adopted in the present paper. The Kepler SNR lies above the galactic plane;

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the density of the interstellar medium surrounding it must be not greater than 0.1 cm^{-3}. It should be noted that the shell-shape structures of the Kepler SNR imaged by radio and X-ray methods are obviously non-spherically symmetric, and the north shell is brighter than the south, as shown in Figures 1 and 2. The flux, corrected for interstellar

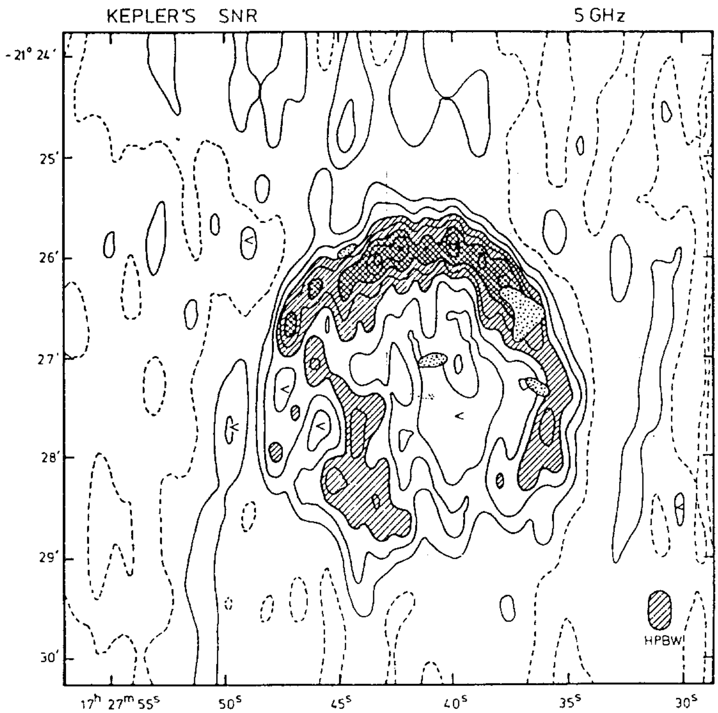

Fig. 1. Contours of X-ray surface brightness for the Kepler SNR (White and Long, 1983).

absorption, is 3.4×10^{-10} erg cm^{-2} s^{-1}, and the total luminosity of X-ray emission is about 1.0×10^{36} ergs s^{-1}.

The event near the north of 42 θ Ophiuchi in 1604 is generally considered as a type I supernova explosion. The event in 1664 has not drawn attention, for it was observed only in Korea at that time and, in addition, only one SNR has been detected in this direction by means of modern astronomical observation techniques. The non-spherically-symmetric features of the Kepler SNR are usually explained as being due to the non-uniform interstellar medium. According to the ancient records, the 1664 supernova was brighter than Sui-Xing (Jupiter) and, therefore, attained − 16 absolute magnitude. The event lasted 8 or 9 months, which was longer than the visual period of the 1604 supernova. The facts that the 1664 event was so bright and that the visual period was so long suggest that it was another supernova. How do we explain these two supernovae explosion events observed visually in the same direction in a time span of 60 years? In terms of the current supernova theory, a supernova explosion leaves a remnant which does not explode again. But a few observed remnants seem more likely than not to be

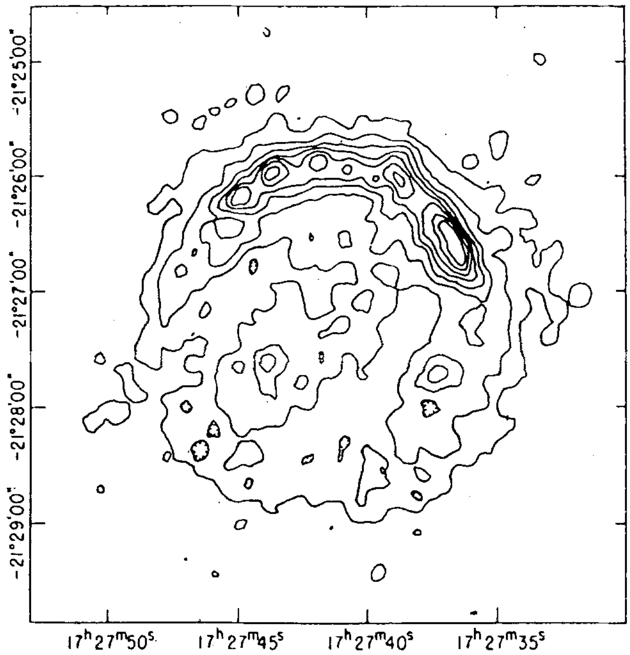

Fig. 2. 'Clean' map of the Kepler SNR (Gull, 1975).

formed from a single outburst event of a supernova, for example, VRO 42.05.01 (Landecker *et al.*, 1982) and IC433 (Hill, 1972). The dynamic characteristics of the central region of our Galaxy are similar to those in elliptic galaxies, where older stars with greater dispersion velocity are crowded together. Some of them are probably the progenitors of type I supernovae. We suggest that there was a supernova explosion in a position close to the north of 42 θ Ophiuchi in 1604, the shock from the explosion propagating into the surrounding medium. Eventually, it induced the outburst of another supernova, which is not very far from the 1604 supernova. The superposition of two explosion events causes the non-spherically symmetric features of the Kepler supernova, which are observed by modern observation techniques.

In the present paper, we will study numerically the dynamic evolution of the Kepler SNR, and apply the two-dimensional unsteady equations of gasdynamics. The calculations deal with the superposition of two supernovae remnants, which lay a distance of about 0.5 parsecs apart, exploding in 1604 and 1664, respectively. The age of the Kepler SNR is about 380 years, and is, therefore, a young remnant. The kinetic energy of the SNR dominates the dynamic behaviour. In comparison with kinetic energy, the loss of energy by emission is small. The calculations suggested that emission energy loss is not important in the dynamic process for such young SNR (White and Long, 1983); therefore, it will not be included in the present calculations. In addition, Gull's radio data show that there are magnetic fields in the Kepler SNR. We suppose the magnetic field pressure to be so small that it would not affect the large-scale dynamic evolution of the Kepler SNR. So the influence of magnetic field is ignored in the calculation of the present step. The 0.15–4.5 keV X-ray emission of the remnant is dominated by the thermal mechanism. Therefore, we deduce the X-ray luminosity and surface brightness distribution of the remnant from dynamic results evolving for 380 years and compare them with observations.

In the next section, the hydrodynamic equations, boundary conditions, initial conditions, and computational method in the present paper are discussed. The numerical results are described in Section 3. In Section 4, the comparison of the calculation results with observations are given. In the last section we discuss our findings.

2. The Model

We adopt the line connecting the two supernovae as symmetric axis z in the cylindrical coordinate system (r, θ, z), and another coordinate r is perpendicular to it. Then, two-dimensional unsteady equations of hydrodynamics are

$$\frac{\partial p}{\partial t} + \frac{\partial \rho u}{\partial r} + \frac{\partial \rho v}{\partial z} = 0\,, \tag{2.1}$$

$$\frac{\partial u}{\partial t} + u\,\frac{\partial u}{\partial r} + v\,\frac{\partial u}{\partial z} = -\frac{1}{\rho}\,\frac{\partial (p+q)}{\partial r}\,, \tag{2.2}$$

$$\frac{\partial v}{\partial t} + u\,\frac{\partial v}{\partial r} + v\,\frac{\partial v}{\partial z} = -\frac{1}{\rho}\,\frac{\partial (p+q)}{\partial z}\,, \tag{2.3}$$

$$\frac{\partial I}{\partial t} + u\,\frac{\partial I}{\partial r} + v\,\frac{\partial I}{\partial z} = -\frac{(p+q)}{\rho}\left(\frac{\partial u}{\partial r} + \frac{\partial v}{\partial z}\right); \tag{2.4}$$

where q is the artificial viscosity term. The equation of state is

$$p = (\gamma - 1)\rho I \tag{2.5}$$

and I denotes internal energy, γ is the polytropic index. The other symbols have the usual meanings.

Now we wish to discuss the boundary and initial conditions. Supernova 1604 is type I; it exploded near the centre of the Galaxy. The progenitor may be an old star with mass of a few solar mass, and $2\,M_\odot$ is adopted as the mass of the 1604 supernova in our calculations. The initial values for computation are given for the estimated quantities at the second year after its explosion. The initial velocity at the surface of the 1604 remnant is assumed to be 7000 km s^{-1} at the surface of the SNR, but zero at the centre, and the initial velocity distribution is linear along the radius. The initial radius and kinetic energy are, respectively, 5×10^{16} cm and 5.85×10^{50} ergs. The internal temperature is estimated to be about 8×10^7 K. The initial pressure is obtained from the equation of state $p = (T\rho R/\mu)(1 + m)$, where m is the average electric charge per ion, μ is the average atomic weight. In consideration of the medium abundant in heavy elements and total electric ionization, we adopt $\mu/(1 + m) = 1.6$. According to the preceding records of ancient observations, supernova 1604 is greater than Tai-Bai (Venus), corresponding (at 5 kpc distance) to the absolute magnitude of -17.69; while the supernova 1664 is mighter than Sui-Xing (the absolute magnitude of which should be -16.09, if the distance were 5 kpc). From this we conclude that the supernova 1604 was 4.4 times as bright as supernova 1664 and the total energy of the former must have been greater than that of the latter. According to these estimates, the mass of supernova 1664 has been adopted as $0.2\,M_{\odot}$; and its initial radius, as 1×10^{17} cm. Similarly, in simplification, we assume that the velocity distribution of matter in SNR 1664 is also linear, from zero at its centre to 11550 km s^{-1} at the surface. The temperature and pressure are given as the same as supernova 1604. Thus, the initial kinetic energy of SNR 1664 equals 1.6×10^{50} ergs, which is about 27% that of SNR 1604. The Kepler SNR has gradually expanded into the surrounding static interstellar medium, which consists of neutral hydrogen atoms with density $n_0 = 0.1$ cm^{-3} and temperature 1000 K.

During the first 60 years after the explosion of supernova 1604, the evolution of the Kepler SNR is described by an unsteady model of one-dimensional, spherical symmetry. After the outburst of supernova 1664, the evolution became two-dimensional unsteady, and the symmetric axis is just the connecting line of these two supernovae. The calculational method of 'fluid in cell', called FLIC method, is used in the present paper (Gentry *et al.*, 1966).

3. Computational Results

The computation radius of Kepler SNR at 380 years after explosion is 2.53 parsecs. Its average expansion velocity, therefore, is 6500 km s^{-1}. The total mass of the remnant is $2.38\,M_{\odot}$, which includes the ejecta $2.2\,M_{\odot}$, while the interstellar medium swept-up by shock accounts for the remaining $0.18\,M_{\odot}$.

The non-symmetric density distribution of the Kepler SNR is shown in Figure 3. In the present paper, supernova 1664 is located 0.5 parsecs away to the north of supernova 1604 and there is, therefore, a stronger compression forming in the north of the remnant. The maximum of density in the north–east shell is 1.8 times as dense as that in the south–east. The densities both in the north and south of the SNR shell are smaller than in north–east or south–east shell. The density distribution is lower in the central region of the remnant, where the density is lower than interstellar medium density surrounding it. To obtain surface density distribution (see Figure 4), we assume the symmetric axis perpendicular to the line-of-sight, along which the remnant is projected.

The X-ray luminosity is calculated from the equation

$$L_x = \varepsilon(T) n^2 v ,$$

where $\varepsilon(T)$ represents the emissivity. The emissivity of 0.15–4.5 keV of a cosmic abundance plasma is 3×10^{-23} ergs cm^3 s^{-1} at $T = 6 \times 10^6$ K (Raymond and Smith, 1977). Considering the major part of the remnant is the ejecta from supernovae but not

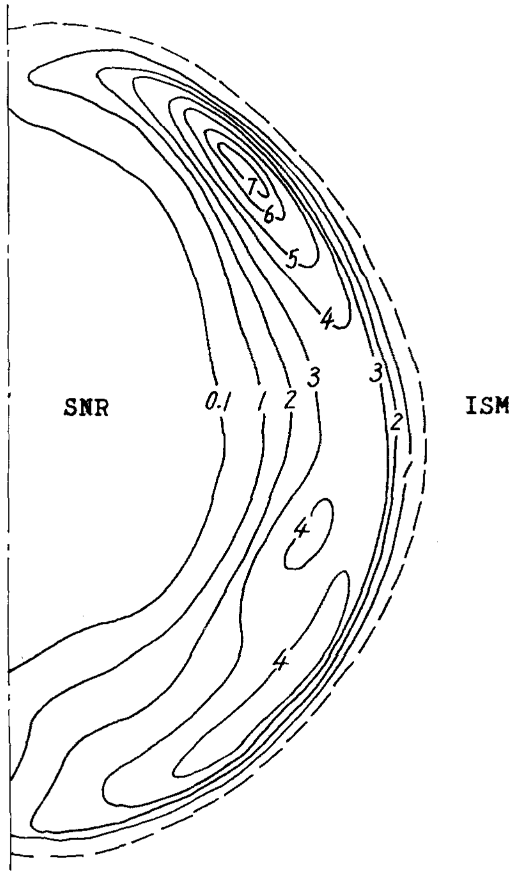

Fig. 3. Computed density distribution (10^{-24} g cm^{-3}).

the mass swept-up by shock, the abundance of medium heavy elements must be greater. If the abundance of heavy elements is increased by 1000 times, the emissivity would be enhanced by a factor of 10–100 (Long *et al.*, 1982). A constant emissivity $\varepsilon(T) = 4.0 \times 10^{-22}$ ergs cm^3 s^{-1} was used to estimate the X-ray luminosity and surface brightness. The number density of electrons, n (per cm^3), is 1.6, which depends on the density ρ and the average ion mass per electron ν in the form $n = \rho/\nu$. From this approach the X-ray total luminosity of the Kepler SNR corrected for interstellar absorption is 0.94×10^{36} ergs s^{-1}. The contours of X-ray surface brightness (see Figure 5) are obtained from projection of the remnant luminosity along the line-of-sight. Generally, the X-ray brightness distribution shows a sphere-shell shape feature. The brightness in the north part is greater than that in south, and the maximum brightness in the north–east shell is about 20–30 times greater than that ahead of the shock, but only about twice as that in the south–east. The weakest X-ray emission is shown near the centre of the supernova of 1664. The X-ray radial surface brightness distribution is presented in Figure 6, while Figures 7 and 8 show the temperature and pressure

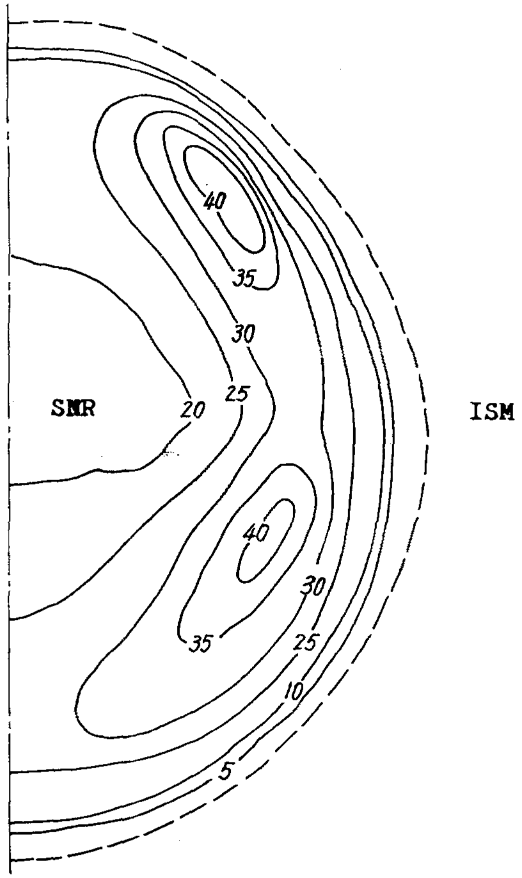

Fig. 4. Surface density distribution (10^{-5} g cm^{-2}).

distributions, respectively. The equation $T = p\mu/\rho R(1 + m)$ is used to obtain the temperature distribution, where $\mu/(1 + m) = 1.5$, and R is the gaseous constant 8.31436×10^7 ergs K^{-1} mol^{-1}. It is obvious that the Kepler SNR has an outer shell with a higher temperature, higher pressure and greater density than in the internal region. According to our model, the temperatures in the outer shell change between 1×10^6–10^8 K and the lowest temperature is about 1×10^5 K. The temperatures in the remaining region are all lower than 5×10^7 K.

The velocity distribution is shown in Figure 9. The values of velocities increase gradually towards the outer edge of the remnant from the centre at the position of second explosion, that is the position of supernova 1664. The front edge of shock is obviously at the position of the outer edge of the remnant, where the velocity changes sharply.

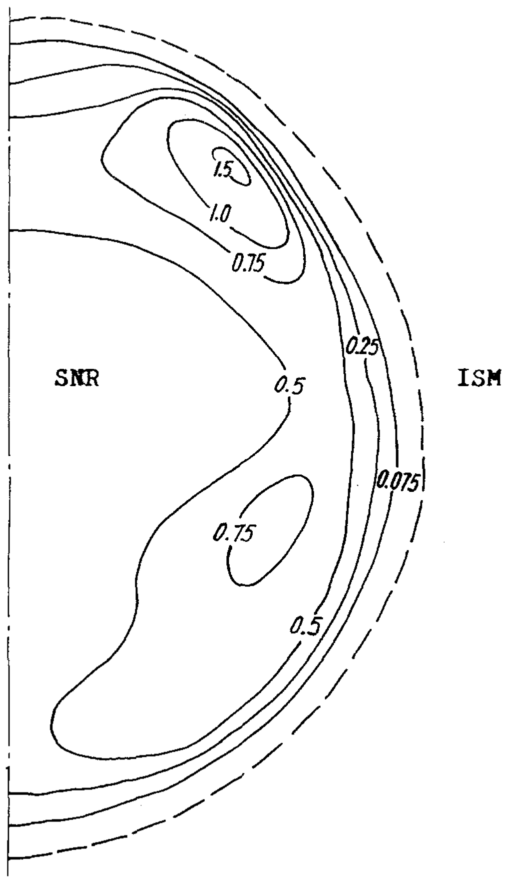

Fig. 5. Computed contours of X-ray surface brightness for the Kepler SNR (10^{-2} ergs cm^{-2}).

4. Comparison with Observations

A circular Kepler SNR with a diameter of 3′ was suggested from the results of observations by radio and X-ray techniques. If the distance between the Kepler SNR and the Sun is about 5 kpc, the associated radius is about 2.18 parsecs. In comparison with the observation, the computed radius of the Kepler SNR is 2.53 parsecs at 1984 for a distance of 5 kpc, which agrees qualitatively with the observations. The X-ray observation gives a luminosity of 1×10^{36} ergs s^{-1}, which also agrees qualitativaly well with the calculation value of 0.94×10^{36} ergs s^{-1}, if the above distance and the greater emissivity are adopted in calculation. The computational X-ray surface brightness distribution is similar to the observed one. There is a bright outer shell, in which the north–east shell is about two times as bright as the south–west, and at the south there is a low brightness void (see Figures 1 and 5). The computational and the observational radial surface brightness distributions are quantitatively similar. However, the quantita-

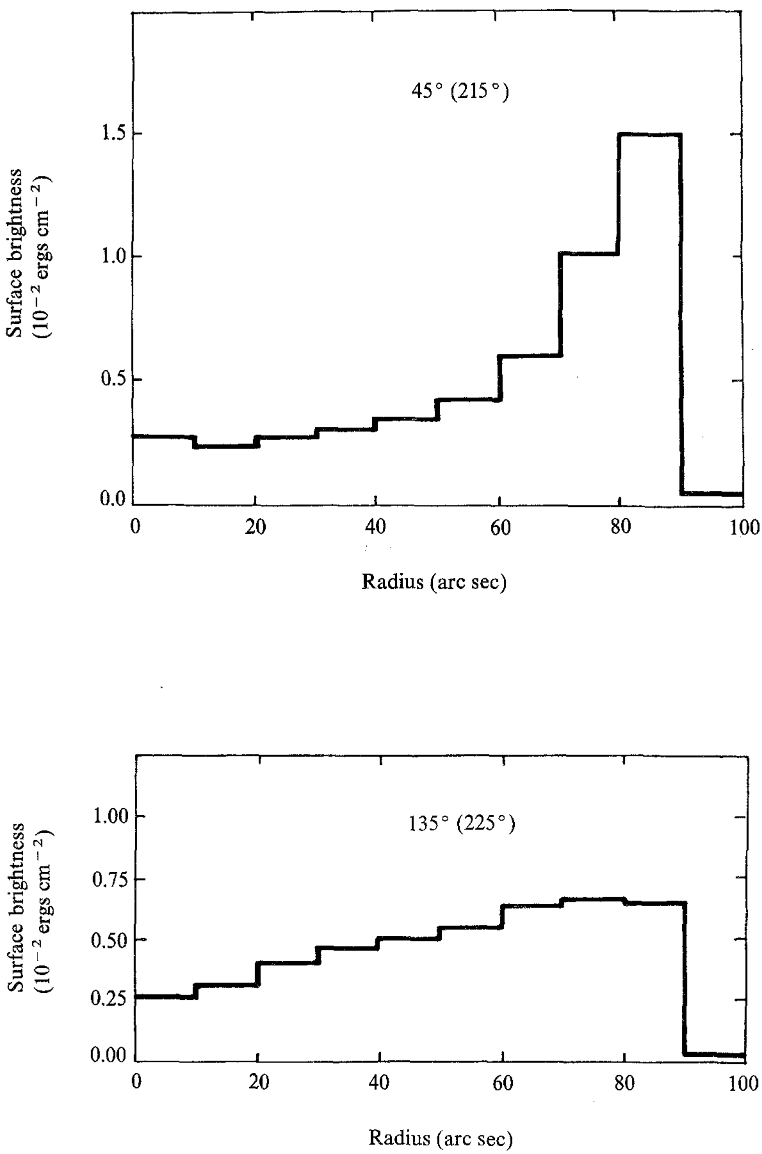

Fig. 6. Radial surface brightness distribution computed for the Kepler SNR.

tive difference between the results is that the observational X-ray emission is a bit brighter along the symmetric axis than the computational results. According to the radio observations, there are three optical filaments with radial velocities of about 200 km s^{-1} lie on the radio shell, and another with radial velocity of about -275 km s^{-1} is close to the centre of the Kepler SNR. If the centre of the remnant is adopted at the position of supernova 1604, the negative radial velocity may be induced by the explosion of supernova 1664. The radial velocities are also very slow ahead of the shock shell.

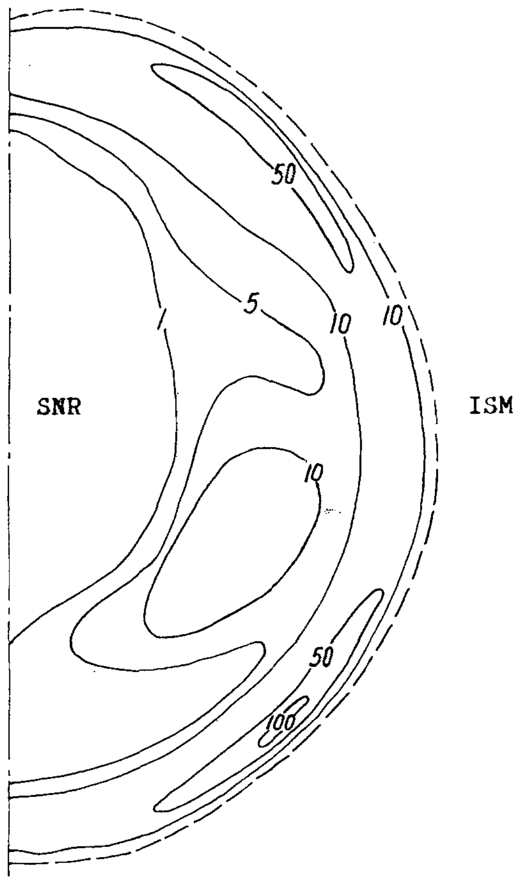

Fig. 7. Computed temperature distribution (10^6 K).

5. Discussion

It is well known that supernova events are extremely complex astrophysics phenomena. The physical conditions of the progenitors of type I supernovae have not yet been determined exactly, either through theoretical deduction or through observations. The detailed results of two-dimensional unsteady gasdynamic calculations depend on the adoptions of many parameters. The initial mass and velocity, hence, the initial kinetic energy, are chosen in terms of common conception. An explanation seems necessary to show the principles used to determine these parameters. First, the distance between supernovae 1604 and 1664 used for the computational model is 0.5 parsecs. Bok and Bok (1981) have expressed the opinion that the number of star encounters with our Sun within a few parsecs is quite large. Therefore, it would be possible that the explosion of supernova 1604 excited the outburst of 1664 in the central region of the Galaxy crowded with much older stars of greater dispersion velocity, though in this region it is most unlikely that an actual collision may occur more frequently than once in

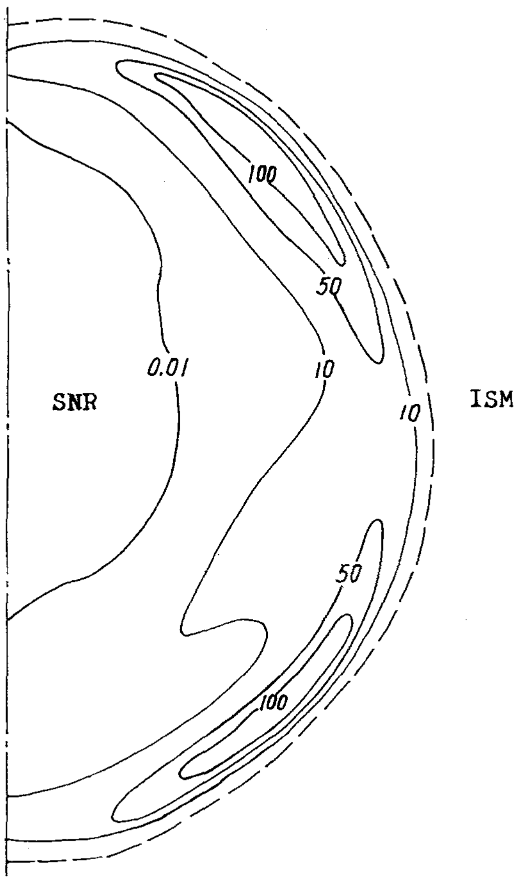

Fig. 8. Computed pressure distribution (10^{-28} g cm^{-2}).

1000 years (Bok and Bok, 1981). Next, to obtain the X-ray luminosity observed, we have to adopt the higher emissivity of 4.0×10^{-22} ergs cm^{-3} s^{-1}. It seems reasonable to do so, for the Kepler SNR is in free-expansion phase. Therefore, the major mass is supernova ejecta, which is abundant in medium heavy elements with enhanced emissivity. It is impossible to distinguish between ejecta and interstellar medium swept-up by the shock in our model, thus the constant emissivity presented above is used for primary estimation. The computed X-ray surface brightness distribution in the central region of the Kepler SNR is obviously different from the observational one. The reason for the difference is probably the influence of a magnetic field which, however, is not included in the present gasdynamic model. The magnetic field will give an anisotropic thermal conduction with smaller conductivity in the direction perpendicular to the magnetic field. In consideration of the possible magnetic field configurations of both SNR 1604 and 1664, the higher plasma temperature in the central region of the remnant could be obtained. In addition, the ejecta clumps observed in the central region imply that the supernova ejecta are not a uniform continuous medium and there would be some ejecta

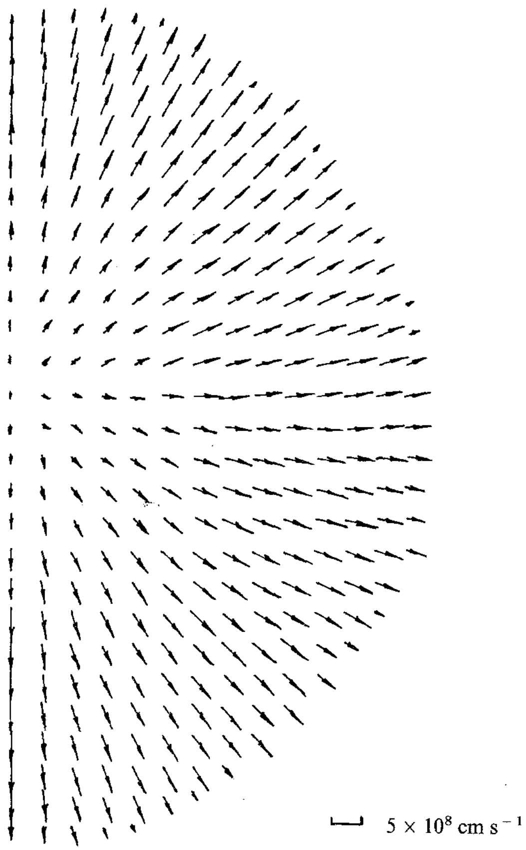

Fig. 9. Computed velocity distribution.

clumps with slower velocity in central portion of a remnant. The abundance of heavy elements of ejecta clumps must be greater than that in the interstellar medium swept-up by shock. However, if a gas cloud was close to the explosion position, an asymmetric X-ray image would emerge. Some current theories suggest that the asymmetric structure of the Kepler SNR has resulted from a non-uniform interstellar medium. However, it is difficult to understand in what conditions the remnant shows such an X-ray surface brightness distribution as the observational one. It would be worthwhile to analyse these problems in detail in future.

Generally, the research of two-dimensional unsteady gasdynamic evolution for the Kepler SNR shows that the remnant is in free-expanding phase and the computed results about the size, X-ray luminosity, surface brightness distribution, and velocity of the remnant are roughly coincident with observations when certain parameters are adopted. The structure features may be explained reasonable by means of our model. This research may justify the ancient records of China and Korea. To probe deeply into the essence of the asymmetric structure of the Kepler SNR, it is necessary to study in detail the influence of stars and the interstellar magnetic field, non-uniform interstellar medium and non-spherically symmetric explosion of a supernova on the dynamic evolution of supernova remnants.

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References

Baade, W.: 1943, *Astrophys. J.* **97**, 119.
Bok, B. J. and Bok, P. F.: 1981, *The Milky Way*, Harvard University Press, Cambridge, Mass.
Gentry, R. A. *et al.*: 1966, *J. Comput. Phys.* **1**, 87.
Gull, S. F.: 1975, *Monthly Notices Roy. Astron. Soc.* **171**, 237.
Hill, I. E.: 1972, *Monthly Notices Roy. Astron. Soc.* **157**, 419.
Landecker, T. L. *et al.*: 1982, *Astrophys. J.* **261**, L41.
Long, K. S. *et al.*: 1982, Columbia Astrophysics Laboratory Rep., No. 213.
Minkowski, R.: 1968, in B. M. Middlehurst and L. H. Aller (eds.), *Nebulae and Interstellar Matter*, University of Chicago Press, Chicago.
Raymond, J. C. and Smith, B. W.: 1977, *Astrophys. J. Suppl.* **35**, 419.
Van den Bergh *et al.*: 1973, *Astrophys. J. Suppl Ser.* **26**, 19.
White, R. L. and Long, K. S.: 1983, *Astrophys. J.* **264**, 196.
Xi, Z. Z. and Bo, S. R.: 1965, *Kexue Tongbao*, No. 5.