Dynamics of Barrel-Shaped Young Supernova Remnants

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Abstract: In this study we have tried to explain the barrel-shaped morphology for young supernova remnants considering the dynamical effects of the ejecta. We consider the magnetic field amplification resulting from the Rayleigh-Taylor instability near the contact discontinuity. We can generate the synthetic radio image assuming the cosmic-ray pressure and calculate the azimuthal intensity ratio (A) to enable a quantitative comparison with observations. The postshock magnetic field are amplified by shearing, stretching, and compressing at the R-T finger boundary. The evolution of the instability strongly depends on the deceleration of the ejecta and the evolutionary stage of the remnant. The strength of the magnetic field increases in the initial phase and decreases after the reverse shock passes the constant density region of the ejecta. However, some memory of the earlier phases of amplification is retained in the interior even when the outer regions turn into a blast wave. The ratio of the averaged magnetic field strength at the equator to the one at the pole in the turbulent region can amount to 7.5 at the peak. The magnetic field amplification can make the large azimuthal intensity ratio (A = 15). The magnitude of the amplification is sensitive to numerical resolution. This means the magnetic field amplification can explain the barrel-shaped morphology of young supernova remnants without the dependence of the efficiency of the cosmic-ray acceleration on the magnetic field configuration. In order for this mechanism to be effective, the surrounding magnetic field must be well-ordered. The small number of barrel-shaped remnants may indicate that this condition rarely occurs.

Keywords: supernova remnant, magnetic field, cosmic ray, dynamics

요약: 본 연구에서는 항아리 형태의 젊은 초신성 진해의 동력학을 설명하기 위해 분출물의 동력적 효과를 고려하였다. 분출물과 성간 물질 사이에 존재하는 접촉면연속면에서 헤일라이-테일러(R-T) 불안정에 기인한 자기장의 증폭효과가 고려되었다. 우주선 입자의 가속을 가능함으로서 합성진과 모형을 만들 수 있었으며 관측과의 비교를 위해 방위각을 따른 전파세기의 비(A)를 계산하였다. R-T 불안정의 결과로 자란 자기의 경계면에서 압축, 전단, 전단의 결과로 층간과 후면의 자기장은 증폭되었다. 불안정의 시간에 따른 변화는 분출물의 감축에 민감하게 의존하며 초신성 진해의 진화와 밀접한 관계를 볼 수 있었다. 자기장의 세기는 초기에 급격히 증가하며 역 층간과 분출물의 동일도지역으로 들어가며 따라 감소하였다. 그러나 이와 같은 초기 자기장 증폭의 효과는 초신성 진해의 후기까지 남아 있음을 볼 수 있었다. 증폭된 자기장 영역에서 적도지역과 극지역의 자기장의 세기의 비는 최대 7.5까지 이룰 수 있었다. 이와 같은 자기장의 증폭은 방위각에 따라 매우 큰 전파세기의 비를 만들 수 있었다(A = 15). 증폭된 자기장의 세기는 수치계산의 분해능에 매우 민감함을 알 수 있었다. 본 연구에서는 우주선 입자의 가속효과가 자기장과 층간과 변이 이론적 각도에 의존한다는 가정 없이도 자기장의 증폭효과가 관측된 항아리 형태의 젊은 초신성 진해를 만들 수 있음을 보였다. 그러나 이와 같은 가정이 효과적이기 위해서는 초신성 진해 주위의 자기장이 잘 정렬되어 있어야 한다. 항아리 형태의 젊은 초신성 진해의 수가 적게 관측되는 것은 이와 같은 조건이 성간에서 잘 이루어지지 않음을 의미한다.

주요어: 초신성잔해, 자기장, 우주선, 동력학

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Introduction

After the highly energetic (≈10^{51} ergs of kinetic energy) explosion of a supernova, the ejected material drives a blast wave into the ambient interstellar medium to produce a supernova remnant. As the supernova remnant shock wave sweeps up the ambient medium, the physical configuration and the morphology of the remnant can be strongly affected by the ambient medium.

Previous studies of the morphology of supernova remnants have simply classified these objects as either “shell-type” or “filled-center”. The shell-type is characterized by a limb-brightened circularly symmetric appearance, consistent with a thin-walled spherical distribution of emissivity and is thought to be a natural outcome of a supernova explosion in a uniform medium, in the absence of a central pulsar. It has long been recognized that in few of the shell-types is the circular symmetry complete. Kesteven and Caswell (1987) found that some degree of bilateral symmetry can be discerned in the radio emission of more than 60% of Galactic remnants and suggested that the majority of shell-type supernova remnants could be bilateral, bipolar, axially symmetric, or, as we shall describe it, “barrel-shaped”. There are three principal observational signs of the barrel-shaped supernova remnant morphology: (a) there is an axis of symmetry, (b) the shell has two regions of low intensity near the top and the bottom of the symmetry axis, and (c) there is a gradient of the radio brightness along the shell (Kesteven and Caswell, 1987; Roger et al., 1988; Caswell et al., 1992). Fig. 1 shows the radio maps of the typical supernova remnants (SN 1006) which demonstrate all features of barrel-shaped morphology: high degree of circular symmetry in radial outline and in radio emission (Reynolds and Gilmore, 1986).

It is generally accepted that the barrel-shaped supernova remnant represents an underlying cylindrical symmetry, the emitting regions corresponding to the curved walls of the cylinder. A barrel-shaped appearance is then produced when the barrel axis is approximately in the plane of the sky, the two bright flanks running parallel to this axis (Roger et al., 1988). Various mechanisms, which might be responsible for the barrel-shaped appearance, have been suggested. These models may be broadly divided into three categories: (a) central pulsar model (Willingale et al., 1996), (b) asymmetric density model (Bisnovaty-kogan et al., 1990), and (c) ambient magnetic field model (Van der Laan, 1962; Whiteoak and Gardner, 1968). It should be noted that it is possible that the different mechanism works at the different evolutionary stage and more than one of these mechanisms work simultaneously.

More recent high resolution observations of radio supernova remnants have revealed strong evidence that the axis of the symmetry of the barrel-shaped supernova remnants is aligned with Galactic plane, supposedly along the direction of the magnetic field (Gaensler, 1998). If the barrel-shaped remnants have the symmetric axis aligned with Galactic plane magnetic field, it means that the galactic magnetic field causes these supernova remnants to appear barrel-shaped. It has long been known that