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Evolution of external magnetic fields of the stars during their gravitational collapse

V. Kryvdyk

Taras Shevchenko National University of Kyiv, 64/13, Volodymyrska Street, 01601 Kyiv, Ukraine

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Abstract

The evolution of external electromagnetic field of the stars during their gravitational collapse has been considered. As follows from the calculations, the external magnetic and electrical field of the stars grows very strong during the gravitational collapse. By decreasing radius more than by three orders, the magnetic field increases by millions of times. The external magnetic field of a star increases by billions of times at the final stage of gravitation collapse, reaching values of 10^{12} Gs near stellar surface. During the collapse the electrical field also increases. At the final stage of the collapse, the electric field increases by billions of times.

Keywords: Stellar magnetic fields; Gravitational collapse; Stellar evolution

1. Introduction

The stars can evolve into one of the three relativistic objects, such as white dwarf, neutron star or black hole (Zeldovich and Novikov, 1977; Shapiro and Teukolsky, 1985; Arnett, 1979) depending on their mass and chemical composition. The precursors of the relativistic massive objects are the red and blue giants, Wolf–Rayet (WR) stars and the supermassive stars (Cherepashchuk, 2003; Eldridge and Tout, 2004; Shapiro and Teukolsky, 1985; Woosley and Heger, 2006). WR stars can be formed from helium cores of massive stars, which have lost their hydrogen shells through exchanging of mass in binary systems, or by way of the mass loss of single stars with the intense stellar wind. WR stars masses are distributed continuously within 5–55 $M_\odot$ (Cherepashchuk, 2003). WR stars experience advanced stages of stellar evolution. They are formed by collapse of carbon–hydrogen (SB) stellar cores, and they can be considered as the immediate precursors of relativistic objects. The collapse of these stars may accompany the burst of a core and formation of supernovae Ib or Ic. Relativistic objects can be formed also as the result of the evolution of massive red and blue supergiants with normal chemical composition. For example, a precursor of supernova 1987 in LMC was supergiant V3I (Chevalier, 1995). O and B stars with masses $M > 10\ M_\odot$ are young massive stars. They generate powerful stellar winds and the intense radiation in the infrared and radio-ranges. The velocity of stellar wind for O stars reaches 3000 km/s, and their loss of mass is about $10^{-5}\ M_\odot$/year. Such rapid mass loss will generate strong thermal radiation (Arnett, 1979; Lucy and Solomon, 1970) due to free-free transitions of the thermal electrons with $T \sim 10^4$ K in stellar wind with Maxwell–Boltzmann distribution (Wright and Barlow, 1975). The flux density of this radiation with frequency ν is $S_\nu \sim \nu^\alpha$ (spectral index of free-free radiation $\alpha \approx 0.4$).

E-mail address: kryvdyk@gmail.com

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2. Observation of the stellar magnetic fields

2.1. Nonthermal radiation from the stars

In addition to thermal radiation, many massive stars also generate nonthermal radiation. This radiation is characterized by considerably less (or even negative) spectral index α and high luminosity temperature (10^4–10^6 K). As follows from Australian radio telescope ATCA the observation (Chapmen et al., 1999), 6 of 36 WR stars are the source of nonthermal radiation. Radio telescope VLA (Chapmen et al., 1999) observation gives a flux radiation from 0.28 mJy to 4.38 mJy for 12 star WR stars. Four of them demonstrated pure thermal radiation (WR 91, 113, 138, 141), seven (WR 8, 79a, 98, 98a, 105, 133, 156) have two-component thermal and non-thermal spectrum, and one (WR 105) has purely non-thermal spectrum. These results indicate that nonthermal spectrum is typical for radio emission of WR stars. Some stars (WR 79 and WR 105) are single and not included in the double system. Observations (Benaglia and Romero, 2003) indicate the nonthermal components in gamma radiation of WR stars with the luminance $(2–8) \cdot 10^{34}$ Erg/s and the spectral index $1.35 \leqslant \alpha \leqslant 0$. The strong variation of the flow of nonthermal radiation of WR stars is observed in many cases. The biggest sources of nonthermal radiation are observed in double systems, which consist of WR stars and massive OB-stars (Aliua et al., 2008; Benaglia and Romero, 2003; Benaglia et al., 2005; Bieging et al., 1989; Blomme et al., 2005, 2007; Blomme, 2005; Cappa et al., 2004; Chapmen et al., 1999; Maggio, 2008). Blomme and Volpi (2014) have shown that synchrotron radiation dominates in radio light curve from a massive O-type binary HD 164794, and in the massive binary system synchrotron emission will be generated due to electrons acceleration to relativistic speeds on the shocks in the colliding-wind region. In the radio catalogue (Bieging et al., 1989) the spectrum of about 40% of the early types of massive stars observed the nonthermal component radiation (Benaglia et al., 2005; Cappa et al., 2004; Chapmen et al., 1999; De Becker, 2007; Dougherty and Williams, 2000). De Becker and Raucq (2013) composed the first catalogue of colliding-wind binaries systems (PACWBs) devoted to particle accelerating, covering spectral classifications from early B-type to evolved WR-stars.

The nonthermal X-ray radiation with hard spectrum from some massive O stars was observed through XMM-Newton telescope (Reimer et al., 2006). The first XMM-Newton observations of X-ray from O-type supergiant's HD 16691 ($O4If^+$) and HD 14947 ($O5f^+$) has reports De Becker (2013). The first observation of very high energetic (above 80 GeV, above 200 GeV and above 600 GeV) gamma-radiation from massive WR stars (WR 147 and WR 146) was obtained through MAGIC telescope (Aliua et al., 2008). The hard (2–12 keV) X-ray emission with flow $F_X = 4 \cdot 10^{-14}$ Erg s^{-1} cm^{-2} from star WR 136 was registered with XMM-Newton telescope (Oskinova et al., 2009). This radiation is generated in plasma with the temperature of around 10^8 K. The strong flow of hard nonthermal radiation with the temperature $T \gg 10^8$ K was observed also from the star WR2 (Skinner et al., 2008). This radiation is generated by moving of the relativistic electrons in the magnetic field, accelerating due to mechanism Fermi on shock waves in stellar wind (Benaglia and Romero, 2003).

2.2. Magnetic fields of stars

The measurements of stellar magnetic field are based on two effects, such as Zeeman displacement of spectral lines and on the observation of the nonthermal radiation from stars with magnetic field.

Zeeman displacement of spectral lines $\Delta\lambda$ in magnetic field (Pacholczyk, 1973)

$$\Delta\lambda \sim B\, g_{\rm eff}\lambda^2,$$

where $g_{\rm eff}$ is the effective factor Lande.

The magnetic fields can also be estimated from the nonthermal radiation, generated by the motion of the relativistic charged particles in magnetic fields. If the particle and magnetic field are in balance, then for the spherical supernova remnants with radius R (Ps), which are located at a distance D (KPs), the magnetic field in the region is determined by the ratio (Pacholczyk, 1973)

$$B = 20(1+k)S_9 D^2 (\varphi R^3)^{2/7}\ \mu\text{G},$$

Here the S_9 is the flux density of the radiation at a frequency of 1 GHz in Jy, φ-factor of volumetric filling, and k is the ratio of the energy of ions density to the energy of electrons density. The magnetic fields in range (25–1000) 10^{-5} Gs for SR with the historically dated was observed by radio observation (Chevalier, 2005; Walder et al., 2012).

In order the synchrotron mechanism of radiation to be effective, the existence of the strong magnetic field in the stellar wind is necessary. The direct measurements of the magnetic field for different stars were made in the last decade (Alecian et al., 2008, 2009; Amiri et al., 2010; Auriére et al., 2007; Berdyugina et al., 2007; Bouret et al., 2008; Cortes et al., 2008; Curran and Chrysostomou, 2007; Donati and Landstreet, 2009; Donati et al., 2001, 2002; Hartigan et al., 2007; Hubrig et al., 2008; Johns-Krull, 2007; Kusakabe et al., 2009; Lébre et al., 2009; Mc Swain, 2007; Neiner et al., 2003; Petit et al., 2008a,b, 2009; Townsend et al., 2008; Valyavin et al., 2006; Walder et al., 2012). These observations are indicative of the presence of strong magnetic fields in different stars. For example, the magnetic fields of the star β Cep (BIIV) equal to 360 Gs (Donati et al., 2001), for the star θ1OriC (O4–6V) about 1100 Gs (Donati et al., 2002), and for ζ Sas (B2IV) about 335 Gs (Neiner et al., 2003). The great magnetic fields are observed in very young massive stars W601 (NGC 6611) (up to 1400 Gs) and OI 201 (NGC 2244) (up to 550 Gs) (Alecian et al., 2008). On the surface