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Magnetohydrodynamic Rebound Shocks of Supernovae

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ABSTRACT

We construct magnetohydrodynamic (MHD) similarity rebound shocks joining 'quasi-static' asymptotic solutions around the central degenerate core to explore an MHD model for the evolution of random magnetic field in supernova explosions. This provides a theoretical basis for further studying synchrotron diagnostics, MHD shock acceleration of cosmic rays, and the nature of intense magnetic field in compact objects. The magnetic field strength in space approaches a limiting ratio, that is comparable to the ratio of the ejecta mass driven out versus the progenitor mass, during this self-similar rebound MHD shock evolution. The intense magnetic field of the remnant compact star as compared to that of the progenitor star is mainly attributed to both the gravitational core collapse and the radial distribution of magnetic field.

Key words: magnetohydrodynamics (MHD) – shock waves – stars: neutron – stars: winds, outflows – supernova remnants – white dwarfs

1 INTRODUCTION

Self-similar evolution of a spherical gas flow under self-gravity and thermal pressure has been studied over past four decades: from simulations and the discovery of Larson-Penston (L-P) type solutions (Bodenheimer & Sweigart 1968; Larson 1969a, b; Penston 1969a, b), to the construction of the expansion-wave collapse solution (EWCS) using the central free-fall asymptotic solution (Shu 1977) as well as to the application of phase-match techniques for constructing infinite series of discrete global solutions including L-P type solutions (Hunter 1977) and solutions for envelope expansion with core collapse (EECC; Lou & Shen 2004). Properties of eigensolutions crossing the sonic critical line were examined (Jordan & Smith 1977; Shu 1977; Whitworth & Summers 1985; Hunter 1986). Self-similar shocks were studied and applied to various astrophysical settings by Tsai & Hsu (1995), Shu et al. (2002), Shen & Lou (2004), and Bian & Lou (2005). While these major results were obtained for an isothermal gas, the counterpart problem with a polytropic equation of state (EoS) was also studied by Cheng (1978), Goldreich & Weber (1980), Yahil (1983), Suto & Silk (1988), McLaughlin & Pudritz (1997), Fatuzzo et al. (2004) and Lou & Gao (2006). In most cases, the polytropic results share a feature that by setting the polytropic index $\gamma = 1$ in the isothermal limit, all asymptotic behaviours approach the isothermal counterpart solutions. However, Lou & Wang (2006) reported new 'quasi-static' asymptotic solutions unique to a polytropic gas with $\gamma > 1.2$ and constructed self-similar rebound shocks for supernovae (SNe).

Chiueh & Chou (1994) studied a self-similar MHD problem by including the magnetic pressure gradient force in the momentum equation. Yu & Lou (2005) improved their formulation and provided a more detailed analysis (see Zel'dovich & Novikov 1971 for a discussion of random magnetic field). Wang & Lou (2006) studied this MHD problem for a polytropic gas and derived the 'quasi-static' asymptotic solutions. Self-similar MHD shocks were explored by Yu et al. (2006). As magnetic field is inevitably involved in SNe and is crucial for synchrotron radiation and cosmic ray acceleration, we construct here rebound MHD shocks with 'quasi-static' asymptotic solutions to model magnetic field evolution in SN explosions.

Type II, Ib, Ic SNe are thought to be caused by gravitational core collapse due to an insufficient nuclear fuel; such collapse creates an over-dense core, which rebounds abruptly initiating a powerful rebound shock. The energetics of sustaining such a rebound shock has been an outstanding problem. We approach this issue in the following perspective. Triggered by such a core collapse, the rebound shock is essentially supported by the neutrino-driven mechanism, and several complicated physical processes are involved in the stellar interior: all four elementary forces and the coupling of various fluids and matters such as baryons, neutrinos, photons etc. (e.g., Janka et al. 2006). We approximate

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such a dynamic system in terms of a single fluid with a polytropic EoS, and treat the shock as an energy-conserved self-similar shock. Conceptually, the 'rebound shock' here refers to a neutrino-driven shock, as opposed to the 'prompt shock' mentioned in Janka et al. (2006). We constructed such a rebound shock (Lou & Wang 2006) to model a SN explosion followed by a self-similar evolution leading to a quasi-static configuration. In reference to the hydrodynamic model of Lou & Wang (2006), the main thrust of this Letter is to construct approximately a self-similar model of a quasi-spherically symmetric rebound MHD shock for a SN explosion, providing the profile and evolution of magnetic field to facilitate future studies of synchrotron radiation and MHD shock acceleration of cosmic rays, and to probe the nature of intense magnetic field of compact stellar objects left behind.

2 FORMULATION AND ANALYSIS

2.1 The Self-Similar MHD Formulation

A quasi-spherical similarity MHD flow embedded with a completely random magnetic field on small scales is formulated the same as in Yu & Lou (2005) and Yu et al. (2006); the key difference here is the polytropic EoS $p=\kappa\rho^\gamma$ instead of an isothermal gas, where p is the pressure, ρ is the mass density, and κ is constant. Using the magnetic flux frozen-in condition, the ideal MHD equations, viz., the mass conservation equation, the radial momentum equation, the magnetic induction equation and the polytropic EoS, can be reduced to two nonlinear ordinary differential equations (ODEs)

$$\alpha'=\alpha^2\left[(n-1)v+\left(2hx+\frac{nx-v}{3n-2}\right)\alpha-\frac{2(x-v)(nx-v)}{x}\right]\times\left[\alpha(nx-v)^2-(\gamma\alpha^\gamma+h\alpha^2x^2)\right]^{-1}, \tag{1}$$

$$v'=\left\{(n-1)\left[\alpha v(nx-v)+2h\alpha^2x^2\right]+\frac{(nx-v)^2}{(3n-2)}\alpha^2-2\gamma\alpha^\gamma\frac{(x-v)}{x}\right\}\left[\alpha(nx-v)^2-(\gamma\alpha^\gamma+h\alpha^2x^2)\right]^{-1} \tag{2}$$

along with a useful relation $m=\alpha x^2(nx-v)$ by the following MHD self-similar transformation in a polytropic gas flow

$$r=k^{1/2}t^nx,\quad u=k^{1/2}t^{n-1}v,\quad \rho=\frac{\alpha}{4\pi Gt^2},\quad p=\frac{kt^{2n-4}}{4\pi G}\alpha^\gamma,$$

$$M=\frac{k^{3/2}t^{3n-2}}{(3n-2)G}\alpha x^2(nx-v)\ ,\quad <B_t^2>=\frac{kt^{2n-4}}{G}h\alpha^2x^2\ , \tag{3}$$

where G is the gravitational constant, M is the enclosed mass at time t within radius r, u is the radial flow speed, $<B_t^2>$ is the mean square of random transverse magnetic field B_t, x is the independent self-similar variable, $v(x)$ is the reduced flow speed, $\alpha(x)$ is the reduced density, $m(x)$ is the reduced enclosed mass, the prime $'$ stands for the first derivative d/dx, k and n are two parameters, and h is a parameter for the strength of $<B_t^2>^{1/2}$. We expediently take $\gamma=2-n$ for a polytropic EoS with a constant $\kappa\equiv k(4\pi G)^{\gamma-1}=p\rho^{-\gamma}$. The magnetosonic critical curve is determined by the simultaneous vanishing of the numerator and denominator on the RHS of eq (1) or (2). The two eigensolutions of v' across the magnetosonic critical curve can be derived by using the L'Hôspital rule (Lou & Wang 2006; Yu & Lou 2005; Yu et al. 2006). The solutions are obtained for $v(x)$ and $\alpha(x)$, and the magnetic field $<B_t^2>^{1/2}$ is then known from transformation (3).

2.2 Analytic Asymptotic MHD Solutions

For $h<h_c\equiv n^2/[2(1-n)(3n-2)]$, eqs (1) and (2) give the magnetostatic solution of a magnetized singular polytropic sphere (MSPS) with $v=0$ and

$$\alpha=\left[\frac{n^2}{2\gamma(4-3\gamma)}+\frac{(1-\gamma)}{\gamma}h\right]^{-1/n}x^{-2/n}\ , \tag{4}$$

$$<B_t^2>=h\frac{k^{2/n}}{G}\left[\frac{n^2}{2\gamma(4-3\gamma)}+\frac{(1-\gamma)}{\gamma}h\right]^{-2/n}r^{2-4/n}\ . \tag{5}$$

There exists an asymptotic MHD solution approaching this limiting form at small x (referred to as the type I 'quasi-static' asymptotic MHD solution), viz., $v=Lx^K$ and

$$\alpha=\left[\frac{n^2}{2\gamma(4-3\gamma)}+\frac{(1-\gamma)}{\gamma}h\right]^{-1/n}x^{-2/n}+\frac{(K+2-2/n)L}{n(K-1)}\left[\frac{n^2/(2\gamma)}{4-3\gamma}+\frac{1-\gamma}{\gamma}h\right]^{-1/n}x^{K-1-2/n}\ , \tag{6}$$

where K is the root of quadratic equation

$$[n^2/2+n(3n-2)h]K^2-(4-3n)[n/2+(3n-2)h]K+n^2+\gamma(2/n-2)(3n-2)h=0\ . \tag{7}$$

When $12-8\sqrt{2}<n<0.8$ and $h_0<h<h_c$, where $h_0\equiv\left[(3+2\sqrt{2})n-4\right]\left[4-(3-2\sqrt{2})n\right]/[2n(3n-2)]$, or when $2/3<n<12-8\sqrt{2}$ for $h<h_c$, eq (7) gives two roots $K>1$, corresponding to two possible 'quasi-static' solutions.

The asymptotic MHD solution at large x is $\alpha=A_0x^{-2/n}+\cdots$ and

$$v=B_0x^{1-1/n}-\left[\frac{n}{(3n-2)}+\frac{2h(n-1)}{n}\right]A_0x^{1-2/n}+\frac{2\gamma A_0^{\gamma-1}}{n[2(n+\gamma)-3]}x^{(2-2\gamma-n)/n}+\cdots\ , \tag{8}$$

where A_0 and B_0 are two constants. Solution (8) at large x can be connected to 'quasi-static' asymptotic MHD solution (6) and (7) at small x by a Runge-Kutta integration (Press et al. 1986), crossing the magnetosonic critical curve either smoothly or with an MHD shock (Yu et al. 2006).

2.3 MHD Shock Jump Conditions

MHD shock conditions (Yu et al. 2006; Lou & Wang 2006) include conservations of mass, momentum, energy and magnetic flux, and in self-similar forms, they appear as

$$\left[\alpha_s\left(n-\frac{v_s}{x_s}\right)\right]_2^1=0\ , \tag{9}$$

$$\left[\frac{\alpha_s^\gamma}{x_s^2}+\alpha_s\left(n-\frac{v_s}{x_s}\right)^2+\frac{h\alpha_s^2}{2}\right]_2^1=0\ , \tag{10}$$

$$\left[\left(n-\frac{v_s}{x_s}\right)^2+\frac{2\gamma}{(\gamma-1)}\frac{\alpha_s^{\gamma-1}}{x_s^2}+2h\alpha_s\right]_2^1=0\ , \tag{11}$$

where quantities in square brackets with superscript '1' (upstream) and subscript '2' (downstream) remain conserved across the MHD shock front indicated by a subscript $_s$. The parameter k changes according to $k_2 = k_1 x_{s1}^2/x_{s2}^2$ on two sides of a shock. For the specific entropy to increase from upstream to downstream sides, $x_{s1} > x_{s2}$ is necessary. MHD shock conditions (9)−(11) lead to a quadratic equation (Lou & Wang 2006); once we specify physical conditions on one side of a chosen shock location, the corresponding quantities $\alpha,\ v,\ x$ on the other side are readily computed.

3 REBOUND MHD SHOCKS IN SUPERNOVA EXPLOSIONS

Various rebound MHD shocks are constructed numerically, parallel to Lou & Wang (2006). With chosen inner and outer radii, e.g., $r_{\rm i} = 10^6$cm and $r_{\rm O} = 10^{12}$cm for neutron star formation, and when the k parameter in transformation (3) is specified, we apply our solutions to a physical rebound MHD shock scenario for SNe (Lou & Wang 2006).

3.1 Final and Initial Configurations

Similar to the hydrodynamic rebound shock model of Lou & Wang (2006), the final configuration (small x) of our rebound MHD shock solutions gradually evolves to a MSPS and is regarded as a remnant compact object after the rebound MHD shock ploughing through stellar ejecta; the initial configuration (large x) marks the onset of gravity-induced core collapse with outer inflows or outflows such as stellar winds or stellar oscillations.

We define the outer initial mass $M_{\rm O,ini}$ and the inner ultimate mass $M_{\rm i,ult}$ the same way as in Lou & Wang (2006) and regard them as rough estimates for the masses of the progenitor star and the remnant compact object. The ratio of the two masses is $M_{\rm O,ini}/M_{\rm i,ult} = \lambda_1 (r_{\rm O}/r_{\rm i})^{(3-2/n)}$ where $\lambda_1 \equiv A_0(k_1/k_2)^{1/n}\{n^2/[2\gamma(4-3\gamma)]+(1-\gamma)h/\gamma\}^{1/n}$ involves parameters of the rebound MHD shock and is equal to the ratio of enclosed masses at the same r. Similar to the result of Lou & Wang (2006), we find numerically that $\lambda_1 > 1$ depends on the choice of solutions, clearly indicating that a rebound MHD shock drives out stellar materials.

By eq (3), the final magnetostatic configuration gives

$$< B_{t,{\rm ult}}^2 >^{1/2} = \sqrt{\frac{h}{G}}\left[\frac{n^2}{k2\gamma(4-3\gamma)}+\frac{1-\gamma}{k\gamma}h\right]^{-1/n} r^{1-2/n}\ . \tag{12}$$

The ratio of initial to final magnetic fields at the same r is $< B_{t,{\rm ini}}^2 >^{1/2} / < B_{t,{\rm ult}}^2 >^{1/2} = \lambda_1$, where $\lambda_1 > 1$ by numerical exploration. Thus a rebound MHD shock breakout process *reduces* the magnetic field by the same ratio of enclosed masses at the same r; yet this decrease in magnetic field is insignificant as compared to the radial variation of magnetic field, i.e., the $r^{1-2/n}$ dependence. As γ approaches 4/3 or $n \to 2/3$, this scaling approaches r^{-2}, while the dependence of enclosed mass on r goes to r^0. For a ~ 10G (0.1G) surface magnetic field at $r_{\rm O} = 10^{12}$cm, we estimate a magnetic field in the interior of the final configuration ($r_{\rm i} = 10^6$cm) to be $\sim 10^{13}$G (10^{11}G), sensible for magnetized neutron stars; if we take $r_{\rm i} = 10^9$cm, then the final interior magnetic field is estimated to be $\sim 10^7$G (10^5G), fairly close to relevant magnetic field strengths of white dwarfs (e.g., Euchner et al. 2005, 2006; Schmidt et al. 2003).

3.2 Evolution of Rebound MHD Shocks

Time evolution of density, velocity and enclosed mass are similar to those described by Lou & Wang (2006). We focus here on the magnetic field evolution. Figure 1 shows a typical time evolution of $< B_t^2 >^{1/2} / < B_{t,{\rm ult}}^2 >^{1/2}$ to complement the $r^{1-2/n}$ behaviour. Magnetic field increases at first, and gradually decreases until reaching the magnetostatic configuration much smaller than the initial configuration in size. In short, magnetic field changes moderately. The crucial point is that the magnetic field varies significantly in r within a star. If we take the magnetic field at the outer boundary to be the surface magnetic field of the progenitor star and take the magnetic field at the inner boundary as the surface magnetic field of the remnant compact star, then a large ratio of $\sim 10^{12}$ appears in forming a neutron star (Lou & Wang 2006). This model feature may explain the intense magnetic field of neutron stars inferred from spin-down observations of radio pulsars. In our scenario, after the passage of such a rebound MHD shock, stellar ejecta detach from the central degenerate neutron star which is thus exposed with a surface magnetic field of $10^{13\sim11}$G. In the same spirit of Lou & Wang (2006), we also suggest the formation of magnetic white dwarfs from the end of main-sequence stars with $6 \sim 8M_\odot$; in this scenario, the surface magnetic field of an exposed central white dwarf is in a plausible range of $\sim 10^{7\sim5}$G (e.g., Euchner et al. 2005, 2006; Schmidt et al. 2003).

The major point to be emphasized is that random magnetic field preexists inside progenitor stars through various dynamo processes. We detect magnetic field strengths of order $10^{-2\sim3}$G on stellar surface and this corresponds to a much stronger magnetic field in the stellar interior with a scaling of $\sim r^{1-2/n}$ shortly after the initiation of core collapse. In addition, the interior magnetic field can be considerably strengthened by the free-fall core collapse preceding the emergence of a rebound MHD shock (see Lou & Wang 2006 for descriptions of the rebound shock scenario and the core collapse process), according to the frozen-in flux and accretion shock conditions. In reality, these two processes happen concurrently to produce the resultant self-similar distribution of magnetic field. In short, the interior magnetic field would be much stronger than the surface magnetic field and can be further enhanced to reach a high-field regime.

The origin of stellar magnetic field was argued by several authors to come from various processes, including dynamo effects and thermomagnetic instabilities (e.g., Reisenegger et al. 2005). Our MHD scenario of interior core collapse and rebound shock appears to grossly match with observational facts. From our MSPS configuration with a random magnetic field strength scaled as $B_t \propto r^{1-2/n}$ in a polytropic gas, we see a real possibility that the interior magnetic field can be actually much stronger than the sur-

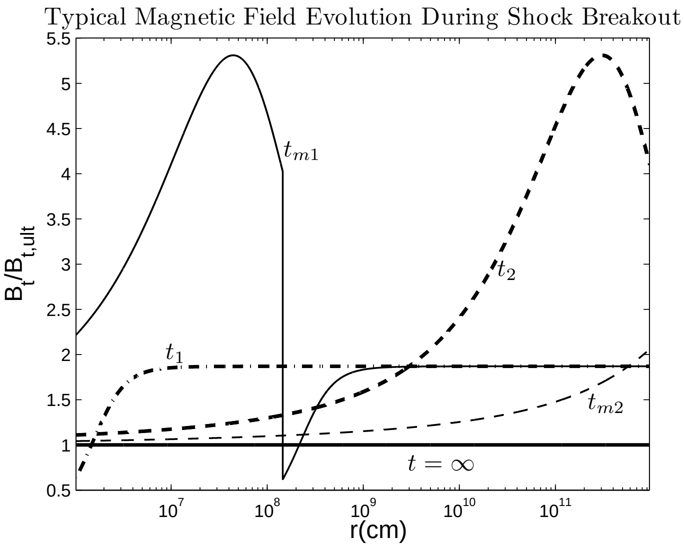

Figure 1. The ratio $B_t/B_{t,\mathrm{ult}} \equiv < B_t^2 >^{1/2} / < B_{t,\mathrm{ult}}^2 >^{1/2}$ is the rms magnetic field strength divided by the corresponding rms magnetic field strength of the final magnetostatic configuration at the same r. This example is constructed by integrating inward from $(x_0\ , v_0\ , \alpha_0)$ on the magnetosonic critical curve and using an eigensolution to match with a quasi-static solution as $x \to 0^+$; we use the solution portion within $x_{s2} < x_0$ for the downstream. We then obtain the upstream point $(x_{s1}, v_{s1}, \alpha_{s1})$ by the MHD shock jump conditions from the values of $(x_{s2}, v_{s2}, \alpha_{s2})$ obtained in the former integration and further integrate outward to determine the upstream solution. The relevant parameters are $\gamma = 1.32$, $n = 0.68$, $h = 0.01$, $k_1 = 7.7 \times 10^{16}$ cgs units, $k_2 = 4 \times 10^{17}$ cgs units, $x_0 = 1.778\ , v_0 = 0.4620\ , \alpha_0 = 0.067$, and $x_{s_2} = 1.1$. Here, $t_1 = 6.61 \times 10^{-5}$s is the time when the MHD shock crosses the inner boundary and is the initial time of application; $t_2 = 4.40 \times 10^4$s is the time when the MHD shock crosses the outer boundary; $t_{m1} = 0.1$s and $t_{m2} = 1 \times 10^8$s are two intermediate times between t_1 and t_2 and t_2 and $t = \infty$.

face magnetic field. Once the onset of a gravitational collapse has been initiated within a magnetized progenitor star and following subsequent free-fall core collapse and accretion shock, an eventual emergence of a rebound MHD shock can evolve in a quasi-spherical self-similar manner and can end up to a MSPS configuration with a high-density compact degenerate object left behind.

4 CONCLUSIONS AND DISCUSSION

We outline and propose the model scenario of a quasi-spherical rebound MHD shock to form high-density compact stars after a gravity-induced collapse in the core of a progenitor star that runs out of nuclear fuels. The stellar interior magnetic field is expected to be enhanced during the core collapse before the eventual emergence of a rebound MHD shock; also the interior magnetic field should be much stronger than the stellar surface magnetic field prior to the onset of a core collapse and during the outward propagation of the rebound MHD shock. Once the magnetostatic configuration of a remnant degenerate star appears, stellar ejecta gradually detach from the compact object, exposing intense surface magnetic fields of $\sim 10^{13\sim 11}$G for neutron stars or $\sim 10^{7\sim 5}$G for magnetic white dwarfs.

Formally, MSPS solution (4) for density diverges as $x \to 0^+$. Conceptually, this can be readily reconciled by the onset of degeneracy in core materials at a nuclear mass density.

In our model, there are two parameters for magnetic field: index n for radial variation and ratio h. While it appears in this Letter that n depends on the stiffness (i.e., γ) of EoS, as discussed below it is in fact a parameter free from the stiffness (i.e., γ). Meanwhile, ratio h represents an ideal MHD approximation that dictates the magnitude variation of random transverse magnetic field; other factors, such as metalicity, differential rotation, convective motions, buoyancy etc. (Janka 2006), are important in generating random magnetic fields inside a star prior to the onset of the core collapse.

In contexts of SN explosions, two-shock models, i.e., models involving a 'forward shock' for the SN remnant shock after the powerful rebound shock crashing into the interstellar medium and a 'reverse shock' produced by the same impact process (see, e.g., Chevalier et al. 1992 and Truelove & McKee 1999), have been studied earlier. The major formulation difference between these earlier works and ours is that they ignored self-gravity of stellar ejecta. By estimates, the self-gravity cannot be obviously dropped and thus these models including forward and reverse shocks would be applicable in the limit of extremely strong shocks in order to ignore self-gravity. Another major difference is that these earlier models focus on circumstellar interactions, while we focus on a rebound MHD shock as it travels within the magnetized stellar interior.

Our polytropic model is currently restricted to $\gamma = 2 - n$ for a constant κ merely for expediency. This constraint can be actually removed if we consistently allow the reduced pressure to be $\propto \alpha^\gamma m^q$ where index parameter $q \equiv 2(n + \gamma - 2)/(3n - 2) \neq 0$ in general and $m = \alpha x^2(nx - v)$ is the reduced enclosed mass. It is then possible for $1 < \gamma < 2$ while $n \to 2/3$. This more general case will be reported separately (Wang & Lou 2006).

Numerical MHD simulations and observations are needed to further test our scenario for rebound MHD shocks in SNe, such as direct or indirect observation of density and flow speed profiles (Lou & Wang 2006) as well as diagnostics of synchrotron emissions caused by relativistic electrons in random magnetic field generated by MHD shocks.

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