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Neutron Star Accretion and the Neutrino Fireball

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Abstract

The mixing necessary to explain the "Fe" line widths and possibly the observed red shifts of 1987A is explained in terms of large scale, entropy conserving, up and down flows (calculated with a smooth particle 2-D code) taking place between the neutron star and the explosion shock wave due to the gravity and neutrino deposition. Depending upon conditions of entropy and mass flux further accretion takes place in single events, similar to a relaxation oscillator, fed by the downward flows of low entropy matter. The shock, in turn, is driven by the upflow of the buoyant high entropy bubbles. Some accretion events will reach a temperature high enough to create a neutrino "fireball", a region hot enough, 11 Mev, so as to be partially opaque to its own (neutrino) radiation. The continuing neutrino deposition drives the explosion shock until the entropy of matter flowing downwards onto the neutron star is high enough to prevent further accretion. This process should result in a robust supernova explosion.

1: Introduction:

Despite years of work by many scientists, the explanation of the mechanism of supernova explosions is still unsatisfactory. See Bethe (1990) for a review. The current explanations depend upon the tantalizingly small difference in energy between the gravitational binding energy of the neutron star and the energy emitted in neutrinos. This small difference, fractionally ~ 3 $\times 10^{-3}$ deposited by neutrinos in the ejecta causes the explosion. Small differences in the modeling of the many physical phenomena (see J. Wilson this volume) causes major difference in the results. one obtains a failed or successful explosion., instead of creating every time, regardless of the initial stellar structure, the relatively standard observed kinetic energy of the ejecta of several FOE (10^{51} ergs). Here we believe that the observations of the "Fe" line profiles and their interpretation in terms of instability mixing are the best signature of the probable mechanism of supernova explosions. This is because the iron, synthesized through Ni^{56} originates at the ejected mass inner boundary and somehow, by major convective "overturn". is transported to close to the outer boundary of the presupernova star.

explain the "iron" lines, leads us to a requirement for a continuing overturn and therefore to a source of heating that lasts much longer than the cooling time of the neutron star. This heating from convectively fed accretion is the logical explaination of the accretion used to drive the explosion in Colgate and White. (1996). (Contrary to frequent miss-conception, these explosions were driven by accretion shock neutrino emission and external neutrino deposition heating.) The mechanism of accretion associated with this convection leads to the concept of a neutrino fireball, or the dynamical collapse of a small fraction of the innermost accreting matter. A neutrino fireball is a region so hot that it is approximately one mean free path thick to neutinos due to its heat alone, ie., due to the neutrinos, electron pairs, and photons.

These accretion events occur episodically like a relaxation oscillator, driven by the low entropy accreting mass flux. A sequence of these accretion events, their associated neutrino deposition heating, and the resulting convection leads to a natural mechanism for augmenting a supernova explosion first initiated by the conventional bounce and neutrino deposition from the neutron star. This mechanism of a sequence of accretion driven neutrino fireballs turns off when an explosion of roughly several FOE has taken place.

The experimental evidence that leads us to the likelihood of this explanation is a requirement for extensive interpenetration or overturn of inner and outer supernova matter. This picture of inter-penetration of matter is different from the usual mixing hypothesis of uniform homogeneous turbulence. The description of non-mixed, interpenetrated matter is necessary to explain the very broad high velocity width iron line profiles from the Ni^{56} synthesized near the core of the explosion. Here we emphasize in addition a second and possibly equally important role of convection, namely feeding the neutron star with low entropy matter so that sequential accretion events can augment the explosion by more efficient neutrino deposition and lead to a naturally self-limiting explosion mechanism.

In section II we will discuss the previous work on modeling "Fe" line widths and the requirement to mix accross the stability boundary between the silicon burning mass cut and the entropy jump between the C-N and He boundary. In section III the structure of a uniform entropy atmosphere in pressure equilibrium with a neutron star surface will derived with a simplified equation of state. In section IV the evolution of such an atmosphere due to neutrino emission and the resulting heating will be given. In section V the ultimate dynamical colapse of such an atmosphere, when the emission rate exceeds the free fall compression heating, will be derived leading to the neutrino fire ball. In section VI the heating due to this neutrino emission and consequences for the explosion will conclude.

II Line Widths and Shifts

Herant and Benz (1991) have shown in detailed calculations that the current interpretation of instability growth of the shocked atmosphere of the supernova 1987A is insufficient to account for the velocity dispersion interpreted from the spectra of iron lines (from the decay of Ni^{56}). The problem is that the Ni^{56} (formed close to the mass cut relative to the neutron star) must be mixed out to the metal-helium and possibly out to the helium-hydrogen boundary. Then subsequent growth of shock induced instabilities must carry it still further out, half way through the hydrogen envelope. This degree of mixing is necessary to give agreement with the observations of the line widths (1) of the 1.257 mm near-infrared line of [Fe II], (Spiromilio, Meikle, and Allen, 1990) and (2) the 842 kev gamma ray of the decay of Co^{56} (Tueller et. al., 1990). Further IR line observations show velocities relative to the center of mass up to 4000 km/s, (Haas, 1991), and all observations show a red shift relative to the observer of up to -800 km/s. This later, almost inexplicable observation, when a blue shift is universally expected, can only be explained by "shredding" the ejecta into discrete dense regions. Both the high velocity observation and the inexplicable red shift have their interpretation based upon instabilities driven by entropy production next to the neutron star. They are evidence for an accretion mechanism as the explanation of the supernova explosion itself. This entropy generation must be an increasing function of time for a time significantly longer, up to an hour, than the time of the neutrino deposition, a few seconds, from the cooling of the neutron star itself. This additional entropy generation we believe comes from the accretion driven by convection.

Initial Models with an Artificial Driver

The simplest model of a supernova explosion is where by some means (presumably a combination of the "bounce shock" and neutrino deposition) a hot bubble of sufficient energy is created suddenly at the inside of the stellar mass to be ejected. In the calculations of subsequent instability growth (Ebisusaki and Shibazaki, 1988: Pinto and Woosley, 1988; Fu and Arnett, 1989; Woosley 1988; Arnett and Fu 1989; Shigeyamama, Nomoto and Hashimoto, 1988: and Herant and Benz. 1991a) the neutron star and its gravity is neglected. This neglect is not justified because the gravity of the neutron star plus that of matter interior to the shock reverses the sign of the acceleration of the matter behind the shock out to a radius within the hydrogen envelope and thus reversing the algebraic sign of the instability growth for a given entropy gradient.

Instability Boundry

However, even if the acceleration becomes reversed at some large shock radius such as to allow instability growth, neverthe less at a smaller radius than the shock radius and within the subsonic matter behind the shock, gravity will always exceed the outward deceleration, that is gravity will be dominant. This is because in a homologous expansion of the subsonic matter behind the shock, the velocity and hence deceleration decreases as R. Since this point, of equal and opposite gravity and deceleration, moves outward in the mass, or Lagrange coordinate, matter that was initially unstable (because of a positive entropy gradient) becomes stable (because of gravity) and no further mixing is expected. (The positive entropy gradient in these models is formed by both the strong shock in a density gradient, $r \sim R^{-3}$, and the fact that the nuclear composition is changing to lower binding energy with radius.) Fig. 2.

Effect of Neutron Star Gravity

The mass fraction most effected by this change in acceleration is that initially closest to the neutron star, or the mass fraction corresponding to the synthesis of Ni^{56} and hence the origin of the later Co^{56}, and Fe lines. Thus in the simplest 1-D models that include a neutron star, one expects this inner mass fraction (of iron) to be strongly affected by the gravity of the neutron star. To add to the confusion of different models, in the models without a neutron star, the sudden initiation of the explosion by the sudden formation of a high entropy bubble also creates a high entropy layer near the boundary of the bubble, which will also be artificially stable. Thus if one is to find a realistic way to mix the Ni^{56} to large radius, one must first find a way to transport it from the radius at which it is formed, ~10 neutron star radii (10^7 cm) out to the boundary between C-O and He (10^{10} cm). Then one must model this with all the proper inner and outer boundary conditions.

Insufficient Mixing without Neutron Star Gravity

Herant and Benz (1991b) have further shown that the expansion of such a high entropy bubble is not sufficient in combination with the shock-created composition dependent instabilities alone to explain the observed iron line widths. In particular the Ni^{56} does not mix beyond the interface of the inside hot bubble and the outside lower entropy shocked matter. The nickle therefore never reaches the slow instabilities driven by the composition gradients. This interface, between the hot bubble and the lower entropy shocked matter is stable, because following the "sudden" formation of the driving hot bubble, this interface slows down as the fluid velocity behind the explosion shock decreases as the shock overtakes an increasing mass. The heavy fluid is thus deceleration the light fluid and thus the interface is stable.

Calculations of Mixing with Neutron Star Gravity

In order to explain this lack of instability and hence lack of mixing of the Ni56 out to large mass, Herant, Benz and Colgate, (1991) have calculated the convection due to the gravity of the neutron star. They have shown that the matter behind the explosion shock (bounce shock) will be supported in pressure equilibrium with the gravity of the neutron star provided the entropy of the shocked matter is high enough.. that is, provided an explosion is first started by the conventional mechanisms. Furthermore, this matter next to the neutron star will be heated by neutrino deposition from the neutrinos from the cooling neutron star, and its entropy is rapidly increased. This increased entropy, derived from this deposition. is enough to drive strong convection in the gravitational field of the neutron star. This convection circulates matter between a region close to the neutron star surface where the neutrino heating takes place and the lower entropy region behind the explosion shock. This circulation replaces high entropy heated matter with lower entropy shocked matter. The low entropy matter has a higher density and paradoxically, in pressure equilibrium, a higher temperature. The combination of both temperature and density greatly increases the neutrino deposition cross section so that a convective loop becomes an efficient means of converting neutrino energy to explosion energy.

Because of the rapid cooling of the neutron star, this source of high entropy matter rapidly decreases with time. With this source of heating alone we expect insufficient mixing to take place and insufficient explosion energy to be produced. However, in this paper we identify an additional source of continuing heating due to the neutrino emission from the accretion of this lower entropy matter circulated from behind the explosion shock. This heating will augment the explosion energy as well as the outward mixing of the Ni56. It continues until the explosion shock itself, in the low density envelope, produces matter of sufficiently high entropy, about 2000 in units of k, the Boltzman factor, such that when and if it reaches the neutron star surface, accretion of this high entropy matter is inhibited (Colgate, 1971).

Figures 3 and 4 show a smooth particle calculation in 2-D of a 60 degree azimuthal wedge of matter in contact with a cooling neutron star. The first figure shows the velocities at 300 ms after bounce time, and the second shows the rising bubbles of high entropy matter. The resolution next to the neutron star is not high enough to resolve the accretion process, claimed here to be high temperature and episodic, nor is the physics in the code sufficient to model a full supernova explosion. There is no accretion and therefore no emission from accretion and so the question of a neutrino fire ball is moot. However, the fact that with just neutron star cooling neutrino deposition the convection is driven with matter (and entropy) preserving flows almost all the way from the neutron star surface to the shock is a major change in the conception of convection. There is negligible mixing and instead low entropy matter from behind the shock can be transported all the way "down" to the neutron star surface. Conversely high entropy matter, heated by neutrino deposition can be transported rapidly away up from the neutron star surface, with small neutrino emission, and transported to close to the shock front. The buoancy of these rising bubbles then drives the shock.

<u>Accretion</u>

The accretion of a dynamically collapsing atmosphere onto a neutron star due to neutrino emission was calculated in Colgate and White, (1966), Colgate (1971), Zel'dovich, Ivanova, and Nadezhin, (1972), and most recently in Chevalier (1989). In the first work the accretion was modeled as a standing shock on the neutron star surface. A fraction of the neutrino emission from this shocked matter was deposited in the in-falling matter and created the explosion. In the second case the collapse of the atmosphere behind the explosion shock due to neutrino emission without regard to the atmospheric structure and evolution was considered. In the third case a small mass atmosphere, < 10-5 M_O was allowed to free fall onto the neutron star; neutrino emission was included, but because of the small mass and consequential high entropy of the post shock matter, the subsequent evolution of the hydrostatic atmosphere was slow and did not reach the limiting temperature of an equilibrium collapsing atmosphere discussed in this paper. The instability was speculated upon without resolution. Nearly the same limitation applied to the fourth case where Chevalier considered the late stage accretion from the explosion shock wave in power law atmospheres. In the last two cases the run-away nature of the collapsing atmosphere was recognized; see also Chevalier and Imamura (1982) Imamura, Wolff, and Durisen (1984), and Bisnovatyi-Kogan and Lamzin (1984). In all these cases the one-dimensional nature of the calculations limited the replacement of any high entropy layer next to the neutron star by convection, and so despite speculations concerning the episodic nature of the the overstability, there was no way to feed the instability with new matter. Instead by feeding low entropy matter by convection to the neutron star surface, a higher mass and temperature atmosphere can build up, leading to a repeat of the non-linear instability.

The Neutrino Fire Ball

An atmosphere in pressure equilibrium on a neutron star and of constant entropy will be hotter at its base as it emits neutrinos. The emission of course reduces the local entropy. Because of neutrino cross sections, the processes runs away, a higher temperature giving rise to a higher neutrino emission rate. The limit of the this processes is when the internal energy is emitted in a free fall time. ie.. when the adiabatic work of compression can not keep up with the emission. This happens when the internal energy is emitted in a free fall time. Since next to a neutron star, this time is of order $3\Delta r/c$, the resulting emission rate is essentially black body. The definition of black body requires close to one mean free path to the emitting radiation, and so the collapsing atmosphere must be close to one mean free path thick to neutrino-pair, neutrino-photon, and neutrino-neutrino scattering. The limiting temperature. $\approx$11 Mev, depends upon both neutrino cross sections and upon a nonlinear evolution of the atmosphere by neutrino emission. There is a minimum mass of the atmosphere, $>3 \times 10^{-4}$ M_0, required in order to reach this limiting condition. (This mass. ΔM, or mass per unit area $\Delta M/4\pi R^2$ must be supported in a gravitational field, g, by the pressure (11/12) aT^4). A fraction of the energy of this neutrino flux will be deposited and a fraction escapes. This division depends upon the structure of the atmosphere above the accretion layer.

The Structure of the Accretion Atmosphere

The flow of matter to the neutron star surface depicted in Fig. 1 is one where a high entropy bubble rises, being displaced by a low entropy downward flow. The heavier matter will spread rapidly, ~c/3, around the surface of the neutron star much like water poured on the floor. When enough matter builds up to a mass ~ ΔM, a runaway collapse will ensue depending upon the initial entropy and entropy contrast, and mass flow rate. The temperature at the base of this atmosphere is so high, transiently (~4×10^{-5} s), that a relatively large fraction of the neutrino energy should be deposited in the high entropy matter (bubble) sitting on top of, and displaced initially by, the low entropy accretion matter. This fractional deposition depends upon the entropy contrast, which determines both its thickness and cross section.

Equilibrium Atmospheres:

We are interested in the properties and ultimately the evolution of an atmosphere supported by a neutron star. The neutron star in turn is cooling due to neutrino emission, but the change in its radius is small, no more than a factor of two, because the extreme internal pressure of the neutron star is supported primarily by degeneracy pressure. The stiffness of the neutron star matter to compression, (high ratio of specific heats or gamma of the nucleon equation of state) makes the neutron star radius only weakly dependent upon the external boundry pressure. Therefore we assume this radius, R_{ns}, is a constant, independent of the properties of the atmosphere resting on it.

The assumptions of an equlibrium atmosphere are:
1. Pressure equilibrium with gravity of the neutron star.
2. The entropy is large compared to unity so that the pressure and internal energy are dominated by photons and pairs $((7/4)aT^4 >> (3/2)n_{nuc}(kT))$.
3. The entropy distribution is either an increasing function of radius, or uniform with radius, because a negative entropy gradient drives convection until the entropy gradient is zero. A positive entropy gradient is stable (see the relavant chapter, Bethe, 1990). Here we assume that the entropy is a constant within a given region of the atmosphere and make up our total atmosphere, if necessary, of finite regions of uniform entropy.

To describe this atmosphere we use an entropy, S, (in units of the Boltzman factor per nucleon) that is approximated from several discrete events in the equation of state in the spirit of Bethe and Wilson, (1985). We identify first the radiation contribution to the entropy where $\Delta S_{rad} = \int dQ/T$. As they pointed out when $Q=aT^4$, or $(11/4)a\,T^4$ when pairs are important, then

$$S_{rad} = (3/4)(11/4)\,aT^3/\rho = 2W_{rad}/W_{nuc} = 1.34\times10^{-11}\,(P^{3/4}/\rho) = 5.02\times10^{8}\,T^3{}_{mev}/\rho. \quad (1$$

In addition the matter entropy can be thought of as composed of its free particle component, $\ln(T/T_0)$, which is almost always close to unity, and the nuclear disassociation energy Fe-He-n,p. At high entropy where $S_{rad}>>1$, these respective transformations occur over a relatively narrow range in temperature. The increament in entropy is relatively fixed and only weakly dependent on the state or adiabat. At $\rho = 10^7$ to 10^9 g cm^{-3}, ΔS_{nuc} (Fe-=He) = 4.1 to 2.84 for this range of density and ΔS_{nuc} (He-n,p) = 11 to 7.14 for the same range of density or a total increament of entopy going from metals to free nucleons of 10 to 15. We will have to include this increament of entropy, but in general at the time of interest of this problem, >2 s, the explosion shock will have reach 10^9 cm and the entropy behind the shock will be greater than 20.

such that using the above $\gamma=4/3$, an adiabatic process, PV^γ = constant. The absolute value of s is in units of "k", the Boltzman constant. Then the equations are greatly simplified by using the above constant γ for a radiation dominated gas, and so we ask what value of s corresponds to where the radiation plus pair energy density equals the particle energy density or $(11/4)aT^4 = (3/2)nkT$, for an atomic weight unity (electrons≈protons≈neutrons). Then s=2. In this case:

$$s=s_oP/\rho^{4/3}, \qquad s_o = 0.79\times10^{-15}\text{ cgs.} \quad (1$$

A: Constant Entropy Atmosphere.

With s independent of R, then:

$$dP/dR = -g\rho = -M_{ns}G\rho/R^2\,. \quad (2$$

Then

$$P= [(M_{ns}G/4)\,(s/s_o)^{-3/4}\,(1/R - 1/R_1) + P_1{}^{1/4}]^4\,. \quad (3$$

where P_1 is the pressure at an outer boundry at R_1. In the limit where the outer boundry is at a large radius relative to that of the neutron star. as is the case of the explosion shock for times longer than 0.01 second, then we neglect $1/R_1$ and $P_1{}^{1/4}$ compared to $1/R$ and $P^{1/4}$. Then we obtain:

$$P = (M_{ns}G/4)\,(s/s_o)^{-3}\,R^{-4}\,. \quad (4$$

$$\rho = (M_{ns}G/4)^3\,(s/s_o)^{-3}R^{-3}\,. \quad (5$$

$$T = (3M_{ns}G\,/(11a))]^{1/4}(s/s_o)^{-3/4}\ R^{-1}, \quad (6$$

and

$$M = 4\pi(M_{ns}Gs_o/4)^3\,(s/s_o)^{-3}\,\ln(R_1/R). \quad (7$$

Thus the temperature at the base of an equilibrium atmosphere increases inversely as the radius and as $s^{-3/4}$.

Thus an isentropic atmosphere leads to a power law distribution of the state conditions. The mass of the atmosphere decreases as s^{-3} and so for high entropy becomes negligably small. The principal counter intuitive effect, however, is that the temperature increases with decreasing entropy, just as a in a normal star, and so neutrino emission at the base of the atmosphere causes it to become hotter and emit neutrinos still more rapidly. This leads to a non-linear collapse of the atmosphere next to the neutron star surface. One also notes that when s approaches unity, near the transition to degenerate neutron star matter, and again assuming pressure equilibrium, the temperature would be extremely high, 80 Mev, as we show later.

Figure 3 describes in an approximate fashion a typical structure of the convecting atmosphere in pressure equilibrium with a neutron star surface at t=2 seconds where a layer of the critical accretion mass ΔM and critical radiation entropy per nucleon, $S \sim 30$ has built up beneath one of high radiation entropy, $S \sim 400$, a bubble, which still further out drives the explosion shock producing lower entropy matter, $S \sim 40$. Here the radiation entropy follows the analysis of Bethe and Wilson (1985) where the radiation entropy, S_r , is considered additive to the matter entropy, and is given by $S_r = 2(W_{rad} / W_{nuc})$, where W is the respective energy per unit volume. In addition one must include the entropy of the nuclear state. The entropy of excited states is small enough here, < 0.5, that it can be neglected but depending primarily upon the temperature, the nuclei may be disassociated with the two primary transitions, Fe - He and He - n,p. Since these transitions occur within a relatively narrow region of temperature, (especially for entropies greater than 10), the entropy increment is a near constant. One has $\Delta S = -\Delta Q/T = -2.8$ to -4.1 for the Fe - He transition for the range of densities 107 to 10^9 g cm-3, and -7.1 to -11 for the He - n,p transition. Some attempt has been made to include these transitions in the figure, but the point is that the figure is meant to be schematic of the process of convection and episodic accretion. The low entropy layer resting on the neutron star will soon collapse (a few x 10^{-2} s) leading to a sudden burst of high energy neutrinos. These in turn will heat some of the top of the low entropy layer and some of the bottom of the high entropy layer. Since this heating occurs in a time short compared to sound traversal, the result will by a local dynamic expansion in a time short compared to neutrino cooling. Buoancy will then carry this high entropy matter away. Steve Bruenn of Fl. Atlantic University is calculating the 1-D behavior of this layer alone.

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