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NEW MECHANISM FOR SLOWING DOWN THE ROTATION OF DENSE STARS*

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ABSTRACT

Weak neutral currents increase the coupling of neutrinos to stellar matter, yet do not inhibit their escape. We propose that this increased coupling transfers angular momentum to the neutrinos which spiral away leaving a slower spinning star.

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I. INTRODUCTION

So far essentially two mechanisms have been advanced as a means by which stars lose angular momentum and slow down: 1) emission of electromagnetic waves and 2) emission of gravitational waves. Here we propose a new mechanism: emission of neutrinos and antineutrinos. We will argue that this mechanism can be more important than either of the other two. It is a new effect predicted exclusively on the basis of the recently observed weak neutral currents.

Neutrinos (from hereon we delete "and antineutrinos") are known to play an important role in stellar cooling (Chiu 1964; Beaudet, Petrosian and Salpeter 1967) and supernova explosions (Wilson 1971, 1974). A large amount of energy E_ν is carried by neutrinos in a very short time (a matter of seconds) during a supernova explosion, while in stellar cooling the rate of energy loss $\dot{E}_\nu$ is much smaller but continues for a very long time (millions of years). Unlike the effect discussed here, both cooling of stellar interiors and blowing-off the envelope in a supernova can proceed via the ordinary charged currents. Neutral currents may increase or decrease the cooling (Mikaelian 1975), but always enhance a supernova explosion because the neutrinos now exert a greater pressure on the envelope by scattering coherently off the heavy nucleii (Freedman 1974).

We propose that these neutrinos, emitted from stars of high density, $\rho \approx 10^{10} - 10^{15}$ gm/cm^3, will carry away angular momentum and leave the star rotating at a slower rate. The reason is the following: between creation and escape, the neutrinos interact rather strongly with the star through

$$\text{Coherent scattering:} \quad \nu A \to \nu A \tag{1}$$

and

$$\text{Elastic scattering:} \quad \nu p \to \nu p, \quad \nu n \to \nu n\ . \tag{2}$$

These reactions of course are allowed only by virtue of weak neutral currents. The neutrinos do not lose energy but rather transfer momentum and angular momentum. The transfer of momentum exerts force on an envelope (Freedman 1974 and Wilson 1974). The torque exerted by the neutrinos slows down the rotation of the star.

There are other interactions, mediated by charged currents, between neutrinos and stellar matter. However these interactions, viz. $\nu n \rightarrow pe$ and $\nu e \rightarrow \nu e$, do not lead to loss of angular momentum because the neutrino is either absorbed in $\nu n \rightarrow pe$ or loses much, about 50% per interaction, of its energy in $\nu e \rightarrow \nu e$. This explains why earlier considerations of stellar opacity to neutrinos could not accommodate rotational effects—most neutrinos escape without any interaction, while the few that do interact are either completely absorbed or come out with very little energy.

We will focus on the escaping neutrinos. Once created, a neutrino will bounce around in the interior of the star a number of times. The exact number depends on the temperature, density, and composition of the star, as well as on the strength of the neutral coupling constants.[1] Eventually it will leave the star. Note that no other particle, except neutrinos, can have the effect discussed here—a type of radiation which interacts without absorption or loss of energy, requirements necessary to pick up angular momentum and escape from the star.

We may speak, therefore, of an "expanding neutrino cloud" inside the star which creates "friction" while expanding until eventual escape. The effect on the neutrino cloud itself is rather obvious: it will start rotating in the same direction as the star, until it escapes, after which it expands in spirals like any free, rotating gas.

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[1] We will not go into a discussion of models. It should be mentioned that the elastic scattering $\nu p \rightarrow \nu p$ has now been observed. See Lee et al. 1976 and Cline et al. 1976.

The reason why this phenomenon should occur only in dense stars is also clear: high densities are needed not only for the production of a substantial number of neutrinos, but also for these neutrinos to sufficiently interact before escape.

In the next section we calculate the angular momentum carried away by the neutrino gas.

II. ANALYSIS

The basic formula is

$$\vec{\tau} = \frac{d\vec{J}}{dt} \tag{3}$$

The calculation of $\vec{\tau}$, the torque exerted by the neutrinos, is very difficult. The hydrodynamic transport equations for neutrino flow have to be solved numerically, and such an effort will not be undertaken here. New calculations on neutrino flow in supernovae have recently been reported by Wilson (1976) and by Arnett and Schramm (1976), but none of them include rotation. This implies that in their picture the neutrinos on the average flow radially out of the collapsing star and hence carry no net angular momentum.

We have argued that the star, which is almost certainly rotating, will transfer some of its angular momentum to the neutrinos which therefore "bend" as they leave the star (Fig. 1). Instead of $\vec{\tau}$ we can easily calculate $\dot{J}_\nu$, the rate at which angular momentum is carried away by the neutrinos. Let us call the bending angle α as in Figure 1; then

$$\dot{J}_\nu = \frac{\pi R}{4c} \dot{E}_\nu \sin\alpha \tag{4}$$

where $\dot{E}_\nu$ is the total rate at which energy is carried away by the neutrinos. In deriving (4) we have assumed axial symmetry and that all neutrinos come out at angle α. Alternatively, α is the average angle of emission in a sense defined below.

The more general expression is

$$\dot{J}_\nu = \frac{R^3}{c} \int \mathscr{E}_\nu n \, d\mathscr{E}_\nu \, \sin\alpha \, d\alpha \, \sin^2\theta \, d\theta \, d\phi \quad . \tag{5}$$

At each point (θ, ϕ) on the surface of the star, $n = n(\mathscr{E}_\nu, \theta, \phi, \alpha(\mathscr{E}_\nu))$ determines the complete spectrum of neutrinos emitted with energy $\mathscr{E}_\nu$ at angle α. This means that

$$\dot{E}_\nu = R^2 \int \mathscr{E}_\nu n \, d\mathscr{E}_\nu \, d\alpha \, \sin\theta \, d\theta \, d\phi \tag{6}$$

determines the cooling rate, and

$$N_\nu = R^2 \int n d\mathscr{E}_\nu \, d\alpha \, \sin\theta \, d\theta \, d\phi \tag{7}$$

is the total number of emitted neutrinos per unit time. θ and ϕ are the usual polar and azimuthal angles, $0 \leq \theta \leq \pi$, $0 \leq \phi \leq 2\pi$, and $-\frac{\pi}{2} \leq \alpha \leq \frac{\pi}{2}$. Equation (4) follows if the α-dependent part of n is assumed to be proportional to a delta function. A more realistic interpretation is to let $\sin\alpha \rightarrow \langle \sin\alpha \rangle$ defined by

$$\langle \sin\alpha \rangle = \frac{4 \int \mathscr{E}_\nu n \, d\mathscr{E}_\nu \, \sin\alpha \, d\alpha \, \sin^2\theta \, d\theta \, d\phi}{\pi \int \mathscr{E}_\nu n \, d\mathscr{E}_\nu \, d\alpha \, \sin\theta \, d\theta \, d\phi} \tag{8}$$

In a supernova explosion the relevant quantity is the total angular momentum carried by the neutrinos:

$$J_\nu = \frac{\pi R}{4c} E_\nu \sin\alpha \quad . \tag{9}$$

Before discussing a numerical example, let us make a few comments on the α-dependence of $\dot{J}_\nu$ or J_ν. Clearly α is the crucial quantity which must differ from zero for any rotational effects to exist—a neutrino gas flowing radially out will have only the effects of cooling the star and exerting pressure on an envelope. The quantity E_ν and $\dot{E}_\nu$ are fairly well known (uncertainties are discussed in the next section). In fact even the energy dependent part of the spectrum $n(\mathscr{E}_\nu)$ is now almost at hand (Wilson 1976 and Arnett and Schramm 1976). This will turn out to be useful information. Rotation is not expected to change $n(\mathscr{E}_\nu)$. What we do not have is the α-dependent part of n.

To assess the importance of J_ν and $\dot{J}_\nu$ it is necessary to compare them with J_s and $\dot{J}_s$, the angular momentum and its rate of loss in a star. In general, we expect

$$\frac{J_\nu}{J_s} = \frac{E_\nu \omega_\nu}{M_s c^2 \omega_s} f(\alpha) \tag{9}$$

and

$$\frac{\dot{J}_\nu}{\dot{J}_s} = \frac{\dot{E}_\nu \omega_\nu}{M_s c^2 \dot{\omega}_s} f(\alpha) \tag{10}$$

with $\omega_s = \frac{2\pi}{T_s}$, T_s = period of rotation of the star, and $\omega_\nu = \frac{c}{R}$. As a function of the bending angle α, $f(\alpha)$ must be a monotonically increasing function from $f(0)=0$ to $f\left(\frac{\pi}{2}\right) = f_{max}$. This follows from the simple physical picture presented here. What about the angle α itself? We expect $\alpha=\alpha(\mathscr{E}_\nu)$ to depend on the neutrino energy $\mathscr{E}_\nu$ as illustrated in Figure 2, that is $\alpha(0)=0$ and $\alpha \to \frac{\pi}{2}$ for large $\mathscr{E}_\nu$. The reason in this case is that all known neutrino interactions are proportional to the energy of the neutrino, so that low energy neutrinos interact very little while high energy neutrinos interact more readily and hence "bend" more. Our ignorance on the amount of bending is reflected by the absence of a scale on the abscissa of Figure 2. Knowledge of $\alpha(\mathscr{E}_\nu)$, coupled with the already available $n(\mathscr{E}_\nu)$, will determine $n(\alpha)$, the number of neutrinos emitted at angle α.

To compare J_ν with J_s and $\dot{J}_\nu$ with $\dot{J}_s$, we will take quantities relevant for gravitational collapse and neutron stars. The following set is an example of reasonable parameters: R=10 km, $M_s=M_\odot=2\times10^{33}$ gm, T_s=1 sec, $\dot{T}_s=10^{-15}$,

$\dot{E}_\nu/V = 10^{18}$ erg/cm^3-sec, and $E_\nu = 10^{52}$ ergs. For a rotating spherical star, $J_s = \frac{4\pi}{5} M_s \frac{R^2}{T_s}$, $\dot{J}_s = J_s(\dot{T}_s/T_s)$, and we come up with

$$\begin{aligned} J_s &= 5\times 10^{45} \text{ erg-sec}, & \dot{J}_s &= 5\times 10^{30} \text{ erg}; \\ J_\nu &= 3\times 10^{47} \sin\alpha \text{ erg-sec}, & \dot{J}_\nu &= 1\times 10^{32} \sin\alpha \text{ erg}. \end{aligned} \tag{11}$$

Even with α as small as one degree, $J_\nu \approx J_s$ and $\dot{J}_\nu \approx \dot{J}_s$.

Of course there is a wide range of rotating dense stars with different parameters. We will next discuss some consequences and tests of the proposed mechanism for these stars to lose angular momentum.

III. APPLICATIONS

The present state of our knowledge about new particles and about the weak interactions does not permit a more detailed investigation of this mechanism. Besides α, E_ν and $\dot{E}_\nu$ still need further study.[2] The reason is again neutral currents: they affect not only the opacity at stellar matter through reactions (1) and (2), but also the production rate of neutrino pairs (Mikaelian 1975). Furthermore, neutral currents allow the creation of new neutrinos much before the previously set threshold based on charged currents alone. For example, ν_μ may now be produced before the so-called "muon threshold" temperature $T \approx \left(m_\mu c^2/k\right) \approx 10^{12}\ {}^\circ K$ (Chiu 1964). Similarly, if new leptons exist (Perl 1975), the corresponding neutrinos ν_L will also be produced at temperatures much lower than their threshold $2\times 10^{13}\ {}^\circ K$. The reason is that charged currents require

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[2] One should not be misled by the notation: $\dot{E}_\nu$ is not the derivative of E_ν, rather it is the rate of cooling in non-violent stars. E_ν is the total energy carried by neutrinos in a stellar explosion like a supernova or in a sudden gravitational collapse.

first the creation of the charged lepton which is very heavy, and then their neutrinos will be produced. Neutral currents by-pass this process completely by creating neutrino pairs directly from ordinary stellar matter at much lower temperatures.

These new neutrinos might not have changed E_ν and $\dot{E}_\nu$ much were it not for an added factor (Mikaelian 1976): they are absorbed much less than ν_e, and thus are excellent carriers of energy and momentum.

We will not discuss other neutral current effects which, like the above, may increase previous estimates of E_ν and $\dot{E}_\nu$. Assuming that a substantial amount of angular momentum can be carried away by neutrinos emitted in dense stars, what astrophysical phenomena are likely to be affected?

The first effect occurs for $\dot{J}_\nu \approx \dot{J}_S$:

1) For the first million years or so after the birth of a neutron star, cooling through neutrino emission far exceeds that of photon radiation, $\dot{E}_\nu >> \dot{E}_\gamma$. This is true even before taking neutral currents into account. If the neutrinos also carry angular momentum, then the rotation of the neutron star will slow down. It is generally believed that pulsars are rotating neutron stars, so that this spin-down might be observable.

The next two effects have to do with gravitational collapse and occur for $J_\nu \approx J_S$:

2) Black holes result from gravitational collapse, a process in which a large number of neutrinos is emitted. A black hole may get rid of most of its initial angular momentum by transferring it to these neutrinos.

3) A similar process occurs in a supernova explosion which results in a neutron star. Different neutron stars will be born rotating at different speeds, depending on how much angular momentum was carried away by the neutrinos

during the explosion. Some supernova remnants show no visible trace of a neutron star—if $J_\nu \approx J_s$, the neutron star might almost come to rest, and of course a non-rotating neutron star would be invisible.

We note that, with this new mechanism for angular momentum loss, many collapsed objects, in particular pulsars, may be more massive than what is presently thought.

Finally, we make a few comments on the observational consequences of the proposed theory. Projects are underway to detect cosmic neutrinos and antineutrinos. This is a vital test for theories of gravitational collapse and stellar cooling. In itself it is a necessary but not sufficient test of the idea that stars lose angular momentum to these neutrinos. If it were possible to do directional neutrino astronomy, it would be very interesting to see if neutrinos are emitted from the center of those supernova remnants mentioned above where no pulsar is "seen", thus substituting for radio astronomy.

The slowing down of young pulsars is perhaps a more accessible signal. Of course it is believed that a pulsar slows down by rotating at an angle to its magnetic field and radiating electromagnetic waves. Denoting the angular momentum lost to these photons by $\dot{J}_\gamma$, we expect that $\dot{J}_s = \dot{J}_\nu + \dot{J}_\gamma > \dot{J}_\gamma$, that is we should find certain pulsars slowing down more rapidly than one expects from pure photon emission.

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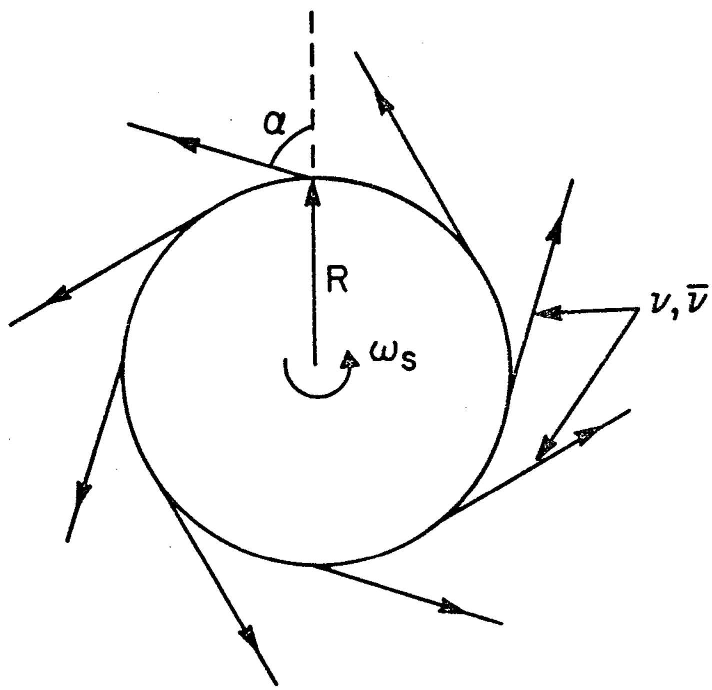

Fig. 1

Top view of a rotating star emitting neutrinos which escape at a bending angle α with the radial direction.

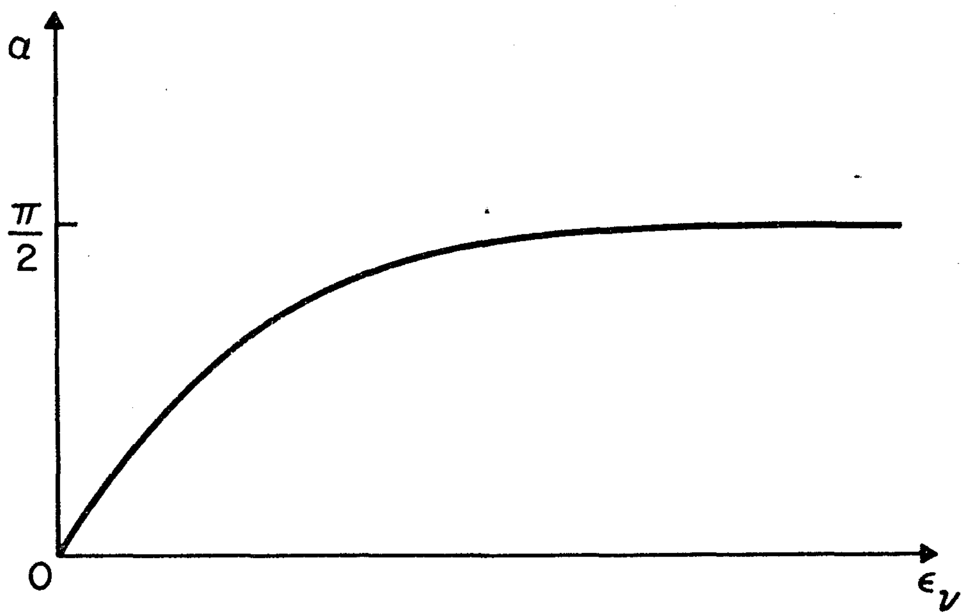

Fig 2

Expected behaviour of the bending angle α as a function of the neutrino energy $\mathscr{E}_{\nu}$.