lar primary flux is a factor of ~100 smaller. If the deduced primary spectrum is in fact the source spectrum, then the acceleration mechanism for these particles is different from the solar acceleration process, which produces steep power-law spectra at these energies.[23]

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RADIO EMISSION FROM MAGNETIC NEUTRON STARS. A POSSIBLE MODEL FOR PULSARS

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We show that radio emission from a neutron star with a magnetic field of 10^9 G or more can account for the radio emission of pulsars. It is suggested that pulsars also emit two bands, one in the uv or optical, and the other in the infrared in the decamicron wavelength range.

Two types of objects have been considered in theories of pulsars, namely, white dwarfs and neutron stars. However, several arguments now seem to exclude the former hypothesis in favor of the nuetron stars: (1) the lack of optical radiation corresponding to white dwarfs[1]; (2) the existence of pulsar NP 0532 in the Crab Nebula supernova remnant[2] and the likely association of another pulsar with the Vela X remnant[3]; (3) the discovery of class-II pulsation with periods ~10 msec in two pulsars[4]; (4) the systematic increase in the NP 0532 periods[5] which has been interpreted in terms of loss of rotational energy of a neutron star[6,7]; (5) the existence of submillisecond variations in pulse intensity, which implies dimensions of $\lesssim$30 km[8]; (6) the fact that no white dwarf can rotate or vibrate with the 0.03-sec period of NP 0532[9]; and (7) the detection of optical pulses from pulsars with a pulse shape essentially that of the radio.[10]

Properties of neutron stars without magnetic fields have been extensively investigated.[11,12]

As discussed in a previous paper[13] and also by many others, a neutron star may possess a very intense magnetic field, 10^9 G or more. In this Letter we present results of an investigation of the radiation from a neutron star possessing such a field. We find that magnetic neutron stars are capable of emitting radio energy with a rate and spectrum comparable with those of pulsars. If our theory is correct, pulsars should also be emitting two or more lines in the ultraviolet and infrared wavelengths. These lines are characteristic of magnetic transitions.

When the Larmor radius of an electron approaches its deBroglie wavelength, the energy of the electron in the plane perpendicular to the field H (the latter is taken to be in the z direction) is quantized and the classical theory of magnetohydrodynamics breaks down. The nonrelativistic expression for the quantized electron energy is[14]

$$E(N,s,p_2,H)=mc^2\left\{\tfrac{1}{2}\left(\frac{p_z}{mc}\right)^2 + \tfrac{1}{2}\left[(2N+1+s)+2\frac{s}{4\pi}\alpha\right]\frac{H}{H_q}\right., \quad (1)$$

where p_z is the z momentum of the electron (the motion of the electron along the field lines is unaffected by this quantization), $\alpha=e^2/\hbar c$, $H_q=m^2c^3/e\hbar=4.414\times10^{13}$ G, and the other symbols have their usual meanings. N is the principal quantum number characterizing the size of the electron orbit and $N=0,1,2,\cdots,\infty$; $s=\pm1$ characterizes the direction of the spin along the field (parallel case: $s=\pm1$). Let $H_9=H/10^9$ G; then the energy differences between different magnetic states with the same z momentum are multiples of $11.6H_9$ eV, and the fine-structure splitting between two states $(N+1, s=-1)$ and $(N, s=+1)$ amounts to $0.0135H_9$ eV. This fine-structure splitting is caused by the anomalous magnetic moment of the electron.[14,15]

In a magnetic field an electron therefore moves in quantized orbits in the plane perpendicular to the field but is free to move in the direction of the field. This means that a "free" electron has only one degree of freedom along the field. The electrons behave like one-dimensional particles, and as a consequence also radiate differently.

The surface density of a neutron star is about 1 g/cm^3. The electrons are not degenerate. The ratio of electron population in the second magnetic state to that in the ground state is $\exp(-Hmc^2/H_qkT)=\exp(-1.337H_9/T_5)$, where $T_5=T/10^5\,°$K.[16] We see that at $H_9=1$, $T_5=1$, most electrons are in the ground state. As we shall see later, this temperature, though considerably lower than an earlier estimate for a neutron star without a magnetic field,[11,12] is more than adequate to explain the enormous radio energy radiated by a pulsar.

There are two fundamental electromagnetic emission processes in intense magnetic fields:

(1) Electrons can make transitions from one state (N,s) to another state (N',s') for $N\neq N'$. Such a transition corresponds to classical synchrotron radiation. It gives rise to photons of energies at multiples of $11.6H_9$ eV. This will be referred to as a magnetic transition. If $N=N'+1$, and $s=-1$ and $s'=+1$, then this transition (referred to as a fine magnetic transition) yields a photon of energy $0.0135H_9$ eV. No continuum emission is possible because of the orbital quantization.

(2) A transition can take place between states of the same quantum number. This type of transition does give rise to a continuum emission. Energy and momentum of the electron, however, are not conserved simultaneously, unless another particle (e.g., a nucleus) is involved. This gives rise to a new kind of bremsstrahlung process,

$$e^- + (Z,A) \xrightarrow{\text{magnetic field}} e^- + (Z,A) + \gamma. \quad (2)$$

The difference between this and ordinary bremsstrahlung process is that in this case, the electron is a one-dimensional particle bound in a magnetic field. We have computed the radiation rate for the continuum process with $N=0$, $s=-1$.[17] The radiation rate (in erg/sec cm^3 sr per unit photon energy range) is:

$$I(E,E_\gamma,\theta)=\frac{16}{\pi^3}N_iN_e\left(\frac{\hbar}{mc}\right)^3\left(\frac{mc^2}{\hbar}\right)Z^2\alpha^3\left(\frac{H}{H_q}\right)\frac{E^{5/2}}{E_\gamma^{\,2}}(mc^2)^{-0.5}\sin^2\theta$$
$$=0.98\times10^{-14}Z^2N_iN_e\left(\frac{H}{H_q}\right)\frac{E^{5/2}}{E_\gamma^{\,2}}\sin^2\theta, \quad (3)$$

where θ is the angle between the emitted photon and the field, E is the energy of the electron, and E_γ is the energy of the photon emitted. N_e and N_i are electron and nucleon (of charge Z) densities, respectively. It should be noted that Eq. (3) does not reduce to the formula for ordinary bremsstrahlung in the limit $H \to 0$, as might be expected. This follows because in an ordinary bremsstrahlung process only the perturbed part of the plane-wave function of the electron contributes to emission (as is well known, a plane-wave electron cannot emit nor absorb a photon).[18] In the case of intense magnetic fields, the electron wave functions are bound-state wave functions in a magnetic field and not plane waves.

Approximating the electron energy E by its average value $\frac{1}{2}kT$ ($\frac{1}{2}kT$ because it is a one-dimensional particle), Eq. (3) becomes

$$I(E, E_\gamma, \theta) = 3\times10^{-28} N_i N_e H_9 Z^2 T_5^{5/2} \nu_8^{-2} \sin^2\theta \quad \mathrm{erg/cm^3\ sec\ GHz}, \tag{4}$$

where $\nu = 10^8\nu_8$ is the frequency. The spectral index is -2 and is quite different from the blackbody case. This agrees with observation as the observed pulsar spectra have indices between -1 and -3.[19]

It is known that the energy emitted by a gas in thermal equilibrium cannot exceed that given by the Planck law. However, departures from thermodynamic equilibrium take place when the magnetic neutron star pulsates along the field direction. During an oscillation, the temperature of the ions and the electrons will change adiabatically. The ions are classical particles, so that $T_i \propto \rho^{2/3}$ where T_i is the ion temperature and ρ is the density. However, in an intense field the electron gas is a one-dimensional gas.[7] Assuming no change in quantum numbers, the electron temperature T_e is proportional to ρ^2. An electron gas initially in equilibrium with the ions will, during the expansion phase of the oscillation, become cooler than the ions. The upper magnetic states will then be overpopulated, and a departure from equilibrium will be set up. Stimulated emission can cause electrons in the upper states to avalanche into states of lower quantum numbers, in a laserlike process. In the contracting phase, matter moves back to regions of high density, and T_e will be greater than T_i, and a superheated electron gas will result. As it will take many collisions with the ions to achieve equilibrium, the most efficient way for electrons to lose energy is via the bremsstrahlung process. Coherent radiation may result in both cases. The density scale height at the surface of a neutron star is only 1 cm, hence an oscillation involving matter up to a depth of a few centimeters with an amplitude of also a few centimeters will pump a sizable fraction of the electrons into the upper states. It is shown[15] that the absorption coefficient vanishes (for the radio case) along the field. If the optical thickness is taken as a few centimeters, then the emitted radio flux is $\sim10^{18}$ erg/cm^2 sec for $H_9 \sim 1$, $T_5 \sim 1$. This can account for the large emission rate of pulsars if the radiating area is $\sim10\%$ of the 10^{13}-cm^2 surface area of the neutron star.

One major theoretical problem remains to be answered: How can this radio emission escape the dense atmosphere of the neutron star? It is well known that the dielectric constant ϵ of an electron gas is given by the equation

$$\epsilon = 1 - (\nu_p/\nu)^2. \tag{5}$$

When the frequency ν is less than the plasma frequency $\nu_p = (ne^2/m\pi)^{1/2}$, then the dielectric constant becomes negative. Consequently no propagation of electromagnetic waves at frequencies below ν_p is possible. The electron density at the surface of a neutron star is $\sim6\times10^{23}$/cm^3 and the plasma frequency is 10^{16} Hz, which is well beyond the uv band. However, in a magnetic field this conclusion has to be modified. In certain directions, propagation of electromagnetic waves with $\nu < \nu_p$ is still possible. In general the dielectric constant in a magnetic field has a complicated expression.[20] However, in our case the dielectric constant can be easily computed when the photon energy is much less than the magnetic transition energy.[21] The electrons then can be regarded as truly one-dimensional particles and they can only move in the direction of the field. Consider two cases of propagation: (1) Propagation parallel to the field. The electric vector of the wave will be perpendicular to the field. Since electrons cannot respond to a perpendicular electric field, the wave can propagate freely along the field lines. (2) Propagation perpendicular to the field. The electric vector will have a component along the field lines, this component can interact with the electrons, and propagation is governed by Eq. (5). An electromagnetic wave propagating in an arbitrary direction can be resolved into two wave components, one propagating parallel to the field and the other perpendicular to it. Only the parallel component can propagate if the frequency is less than the plasma frequency.

Equation (4) shows that bremsstrahlung emission in a magnetic field will in general not be in the direction of the field. However, because of the effect mentioned in the last paragraph, only the wave component parallel to the field can propagate into space. The absorption cross section due to the inverse reaction of (2) vanishes along the direction of the field.[17] A small absorption cross section implies that the radiation rate is the same as the production rate, and the spectrum of radiation should somewhat reflect the production spectrum. A magnetic neutron star will therefore not radiate as a black body.

We also expect that emission from a magnetic neutron star will occur predominantly in the polar region, where field lines diverge into space. The radiation will then concentrate in a narrow cone defined by the field configurations near the pole. A magnetic neutron star will thus not radiate isotropically, but preferentially in some directions. If the star rotates, this narrow cone sweeps through space, producing a sharp radio pulse ("searchlight effect"). We thus expect that some pulsars will not be detectable because we are outside their sweeping pattern. Maran[22] estimated that due to beaming, at most 1000 pulsars may be observed out of a possible 10^4 pulsars in our galaxy.

Magnetic neutron stars can only radiate near the pole. Such a star will have a very unstable envelope. Tidallike oscillations may take place, and this may be the source of the millisecond pulsations. The period of tidal pulsations will be quite different from the period obtained assuming a pure radial pulsations. Our calculation[17] showed that bremsstrahlung emission from a single electron in a magnetic field is almost 100% linearly polarized. Through processes of stimulated emission, coherent polarization may be possible. This problem will be discussed at greater length in a separate paper. However, if our interpretation of pulsars as magnetic neutron stars is correct, pulsars should also radiate emission lines due to magnetic and fine-magnetic transitions. Because of large-scale field inhomogeneities, these lines will be smeared into bands. The wavelengths of these bands will inform us of the strength of the field according to the equations, for magnetic transition,

$$H_9 = (1069\ \text{Å})/\lambda \quad \text{(uv or optical)}; \tag{6}$$

for fine-magnetic transition,

$$H_9 = (91\ \mu)/\lambda \quad \text{(infrared)}. \tag{7}$$

The detection of the magnetic transition line may be difficult if the field strength exceeds 1.2×10^9 G due to interstellar absorption of uv photons with energies above the hydrogen ionization energy. The fine-magnetic transition will give rise to infrared lines in the decamicron range.

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POSSIBILITIES OF FORMING A COMPRESSED ELECTRON RING IN A STATIC MAGNETIC FIELD*

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A method of forming a compressed electron ring for an electron ring accelerator in a static rather than pulsed magnetic field is proposed. Advantages of this method as well as some problems and possible solutions are discussed and results of computer studies are presented.

After its proposal by Veksler[1] in 1956 substantial interest has developed recently in the electron ring accelerator as a source of high-energy protons, and extensive study programs are now under way at Dubna[2] and Berkeley.[3] In the schemes under investigation a high-intensity, 4.5-MeV electron beam is injected into a betatron-type magnetic field produced by solenoidal coils.[4] After injection the magnetic field is pulsed from a few hundred gauss to some 20 kG thereby compressing the electron ring adiabatically to a final diameter of about 7 cm and an energy of 23 MeV. A stream of neutral hydrogen is injected and protons formed through ionization are trapped in the deep potential well of the high-density electron ring. Acceleration of the protons to high energies is then accomplished either through simple expansion of the electron ring in the magnetic fringe field or by means of a linear accelerator.

We are proposing an alternate compression method by which the electron ring is formed in a static magnetic field. As an example, in this scheme the high-intensity beam from a pulsed, 25-MeV electron linac (pulse width about 10 nsec, corresponding length 3 m) is injected axially into a solenoidal magnetic field as illustrated in Fig. 1. In what is equivalent to a reversal of the expansion process the initial longitudinal momentum $p_{\parallel}$ of the electrons is transformed into transverse momentum $p_{\perp}$ resulting in the formation of a compressed electron ring in the high-intensity-field region (20 kG) at the center of the solenoid. At this point, neutral atoms can be injected, and acceleration via expansion or in a linac would be the same as in the Dubna-Berkeley scheme.

Under adiabatic conditions the magnetic flux linked by an electron trajectory is a constant. An electron with transverse momentum $p_{\perp i}$ and radius of curvature R_i at some initial point ($z = z_i$) in the fringe region of the solenoidal field will have momentum $p_{\perp c}$ and radius R_c in the compressed state at the center of the solenoid ($z = 0$) as determined by the relation

$$\frac{p_{\perp c}}{p_{\perp i}} = \frac{R_i}{R_c} = \left(\frac{B_c}{B_i}\right)^{1/2}, \tag{1}$$

where B_i and B_c is the magnetic field strength at the two points.

If $E_T = E_0 + T$ is the total energy of the electron, $\gamma_T = E_T/E_0 = (1-\beta_T^2)^{-1/2}$, $\gamma_{\parallel} = (1-\beta_{\parallel}^2)^{-1/2}$, and $\gamma_T = \gamma_{\parallel}\gamma_{\perp}$, then relativistic kinematics relates the longitudinal momentum $p_{\parallel c}$ at $z = 0$ to

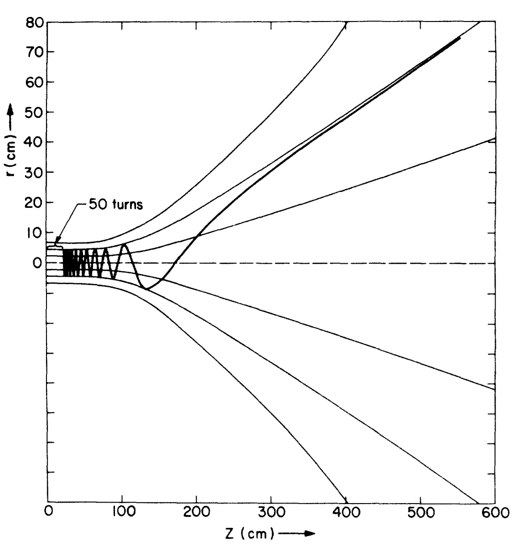

FIG. 1. Electron trajectory in solenoidal fringe field.