THE EFFECT OF MAGNETIC FIELDS UPON COSMIC X-RAY SPECTRA

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ABSTRACT. The effect of strong magnetic fields (B $\gtrsim 10^{11}$ *Gauss*) upon various atomic line emission mechanisms in the X-ray range is considered, in particular for H and H-like or He-like ions, and a discussion of the detectability and significance of possible measurements is given. The cyclotron mechanism, the one- and two-photon scattering and the bremsstrahlung effects in a strong B are reviewed, as well as the role they play in determining X-ray spectra. These considerations are applied to typical models of X-ray pulsars and Gamma-ray bursters, contrasting observations of magnetic related features to the present theoretical understanding of these objects.

1. INTRODUCTION

Magnetic effects in the X-ray spectrum of cosmic sources are of interest in some white dwarf sources ($B_* \lesssim 10^{7-8} Gauss$), and are of major importance in neutron star sources such as accreting or rotation powered pulsars ($B_* \gtrsim 10^{11-12} Gauss$) and possibly Gamma-ray bursters. In this paper we shall concentrate on the latter type of high field objects. In these sources the magnetic field plays the leading role in determining the pulsations by which these objects are identified, and in those which are in binaries this allows one to determine such fundamental parameters as the neutron star mass, c.f. Joss and Rappaport, S., 1984, Mészáros, 1984. In most of these sources the cyclotron ground harmonic is in the X-ray range and the magnetic effects play a major role in the production of photons and in shaping both the line and the continuum spectrum. In what follows we shall describe the current understanding of the physics of strong magnetic fields upon the plasma emission mechanisms, as well as upon the radiative transfer, and how this affects the modeling of accreting pulsars and Gamma-ray bursters.

2. ATOMIC LINES IN A STRONG B-FIELD

In a strong magnetic field, the shape of the probability distribution of the electrons around a nucleus gets elongated along the field lines. A rough criterion for the onset of this is obtained by comparing the energy of the free electron ground cyclotron harmonic, $E_c \simeq 11.6 B_{12} keV$ with the approximate field free line energy $E_l(Z) \simeq 0.0136 \epsilon Z^2 keV$, where ϵ is the line energy in Rydberg units. Magnetic effects are important for atoms whose nuclear charge Z is

$$Z \lesssim 29 (B_{12}/\epsilon)^{1/2} . \tag{1}$$

2.1 The Hydrogen Atom

In the simplest case of the Hydrogen atom, a non-perturbative approach to the magnetic field effects leads to replacing the usual n_p, l, m quantum numbers with a new set n, m, ν, where n is the Landau quantum number, m is the z-projection (along B) of the angular momentum, and

ν is the number of nodes of the longitudinal wave function, c.f. Canuto and Ventura (1973). For $B \gtrsim 10^{11-12}G$, the atom is usually in the state $n = 0$, and the line structure is characterized by the m-bands, the lowest of which are $m = 0, -1, -2, ...$ Within each m-band there is a tightly bound $\nu = 0$ state, whose binding energy is increasingly stronger with increasing field (compared to the field-free H), and a series of $\nu > 0$ states which are called "hydrogen-like", whose energies look like blue-shifted and red-shifted Lyman, Balmer, etc. states, with however different energy and intensity ratios, c.f. Rösner, *et. al.*, 1984. As the magnetic field is increased gradually from zero, the energy levels split first into the usual linear, then quadratic Zeeman sublevels, and as the field is further increased they gradually rearrange themselves into a completely different pattern characterized by the magnetic quantum numbers n, m, ν. For the Hydrogen atom this occurs above $\beta = (B/4.7\ 10^9G) \gtrsim 1$. The dipole transitions occur for $\Delta m = 0, \pm 1$, but the $\Delta m = 0$ are the strongest, since the $\Delta m = \pm 1$ involve the transverse dipole moment, which is supressed by the magnetic field, e.g. Wunner and Ruder, 1980. The strengths are somewhat lower than in the field-free case, but not much. The $\Delta m = 0$ transitions are linearly polarized and have a directionality $\propto sin^2\theta$, while the $\Delta m = \pm 1$ are circularly polarized and $\propto (1 + cos^2\theta)$, as in the Zeeman effect. The tightly bound transitions (involving $\nu = 0$) can be in the range 0.2-0.5 keV for $B_{12} \gtrsim 1$, while the hydrogen-like ($\nu > 0$) transitions are in the eV range. The former would be accessible to AXAF or ROSAT, while the latter would be in the province of HST or HUT.

2.2 Hydrogen-like and He-like Heavy Ions

The pioneering work in calculating energy levels of various atomic species in pulsar magnetic fields dates back to Ruderman and Sutherland (1975), and a fair amount of detailed work has been done since then. For hydrogen-like ions, the energy levels and transition strengths can be scaled from those of the hydrogen atom according to

$$E_m(Z,B) = Z^2 E_m(Z=1, B/Z^2) \quad , \quad f_{\tau,\tau'}(Z,B) = f_{\tau,\tau'}(Z=1, B/Z^2) \ ,$$

c.f. Ruder *et. al.*(1981). The level structure is similar to that of the previously described H-atom. For Fe^{25+}, most of the low lying levels are in the keV range, with significant departures from the field-free values occuring for $\beta \gtrsim 20$, or $\gtrsim 10^{11}G$. The strongest transition is the (magnetic) 001 → 000, which for fields of order $10^{12}G$ would produce about $10^{15}s^{-1}$ photons per atom, assuming the level population on average to be one electron. These are fairly substantial deexcitation rates. As in the H-atom itself, there are also continuum limits, e.g. a Lyman-like, Balmer-like, etc limits.

A procedure for calculating the energy levels of He-like atoms in a strong field based on the Hartree-Fock approach has been discussed by Pröschel *et. al.*(1982). They give the ground state energies of all He-like ions up to and including Fe^{24+}, as a function of the magnetic field strength. For fields in excess of about 5 $10^{11}G$ ions heavier than C^{4+} have ground state energies above keV values, increasing with field strength. Thus, at $B \simeq 10^{12}G$, Fe^{24+} has its ground state energy at 32.1 keV. A different method of calculation, based on a density functional, has also been discussed by Kössl *et. al.*(1986).

The most basic observational limitation to the detection of atomic X-ray lines is that one needs to avoid smearing by Compton scattering, and this favors the observational candidates with lower luminosities, $L_x << L_{Edd}$. As an example (Ruder *et. al.*, 1981) consider the low luminosity X-ray pulsar 4U0900-40, where if one takes an emitting area about $10^{10}cm^2$, a distance about 1 Kpc, a solar abundance of Fe and estimating from Saha's law the ratio of excited to ground level population to be about 10^{-4}, one gets an expected line photon flux of about $10^{-3}cm^{-2}s^{-1}$, with $\Delta E/E < 0.1$. This effect should be detectable with present instrumentation.

3. CYCLOTRON AND CONTINUUM RADIATION MECHANISMS

Free electrons have unquantized momenta along the magnetic field (z-axis) but are restricted in the transverse plane to discrete energy states, the Landau levels. In units of the critical magnetic field $B_q = (m^2c^3/e\hbar) = 4.413\ 10^{13}G$ (at which the ground cyclotron frequency equals the electron rest energy), the energy levels are given by

$$E = \left[p^2c^2 + m^2c^4(1 + 2j\frac{B}{B_q})\right]^{1/2} \tag{2}$$

where $j = n+s+\frac{1}{2} = 0, 1, 2, .., s = \pm\frac{1}{2}$ and $n = 0, 1, 2, ...$ In the non-relativistic limit, the levels are evenly spaced, with ground level energy energy equal to the separation of subsequent levels given by

$$\hbar\omega_c = \frac{\hbar eB}{mc} = 11.6B_{12}\ keV\ . \tag{3}$$

This quantizing aspect of the magnetic field has a profound influence upon all elementary processes involving typical energies not much larger than given by equation (3). Another significant departure from non-magnetic conditions is that the plasma becomes anisotropic, all rates and cross sections depending not only on energy but also on direction of the photon or particle respect to the magnetic field direction. In addition, for all processes involving photons, a significant polarization dependence is introduced for photon frequencies $\omega \lesssim \omega_c$ given by equation (3). It is easy to visualize the physical basis of this dependence, if one considers that a photon polarized with electric vector parallel to the field (ordinary photon) can interact with the electron as essentially as in the absence of a field (since it moves the electron along B) whereas a transverse electric field (extraordinary photon) tries to move the electron in the plane transverse to B, where the phase space of the electron is limited by the discrete Landau orbitals unless if $\omega \gg \omega_c$.

3.1 Cyclotron and Bremsstrahlung Processes

The frequency of collision of electrons with other charged particles, for instance, becomes a jagged rather than a smooth function of the particle energy of motion, exhibiting cyclotron resonances affecting both the Coulomb thermalization rates as well as the collisional excitation rate responsible for the bremsstrahlung process (Ventura, 1973, Bussard, 1980). The radiative deexcitation rates are extremely fast, $t_{rad} \simeq 10^{-18}(B/B_q)^{-2}s$, shorter than collisional excitation rates by many orders of magnitudes under typical X-ray pulsar densities and temperatures. The usual cyclotron or synchrotron radiation rates, calculated using an equilibrium excited level population, do not usually apply since at keV temperatures the electrons are predominantly in the ground level $n = 0$, and return there radiatively as soon as excited. The equivalent of the "cyclotron" emission mechanism, related by Kirchoff's law to a corresponding absorption coefficient, is therefore the Bremsstrahlung process (Nagel and Ventura, 1983). This consists of both a continuum part, related to knock-on excitations in the longitudinal component of the electron momentum, and to transverse excitations which give rise to cyclotron resonances, e.g. Pavlov and Panov (1976). This is the major source of seed photons both at the resonances and in the continuum.

3.2 Compton Scattering

Comptonization, or the reshuffling of photons in energy space by Compton interactions is a major effect in X-ray sources, whether magnetized or not, since the scattering opacity usually dominates over the absorption and emission opacities. A recent review of this process has been given by Pavlov *et. al.*(1988). In a magnetic field, the scattering opacity is both angle and frequency dependent (Canuto *et. al.*, 1973), and has a rather interesting dependence on the polarizability of the plasma and of the vacuum provided by virtual $e^{+}-e^{-}$ whose density depends on the magnetic field strength (Gnedin *et. al.*, 1978, Mészáros and Ventura, 1978, 1979). The energy of the resonances depends also on the angle θ between photon and field, which contributes to spread the resonance in the diffusion regime, in addition to the thermal Doppler broadening (which in this case is θ-dependent, thermal motions being along the z-axis). Ordinary and extraordinary polarization photons have rather different scattering cross sections at $\omega \ll \omega_c$, the extraordinary being supressed by a factor typically of the order $(\omega/\omega_c)^2$ respect to the Thomson value. Relativistic effects can become important at temperatures above about 10 keV, c.f. Herold, 1979, Bussard *et. al.*, 1986, Daugherty and Harding, 1987.

3.3 Double Compton and Two-photon Processes

In general two-photon processes are down by one factor of α_f respect to the corresponding single photon processes. However, in a magnetic field the cross section is resonant at particular photon frequencies, which can compensate partly for the decrease in cross section. In fact, the one photon scattering starting with an electron in the ground Landau level and a photon not far from resonance, which leaves the electron in the first excited state with emission of a soft photon $(\omega_c, 0 \rightarrow \omega_s, 1$, where $\omega_s \ll \omega_c)$, has a cross section roughly comparable with that of the normal $(\omega, 0 \rightarrow \omega', 0)$ scattering. The excited final electron deexcites very fast by emission of a second, resonant photon (Bussard, Mészáros and Alexander, 1985), and this provides a substantial source of soft photons, in addition to Bremsstrahlung. This process is related to the two-photon decay from an excited state (Kirk and Melrose, 1986a,b). At low frequencies, the effectiveness of this mechanism as a photon source is limited by the inverse process, saturating at the blackbody level, but it can still exceed the bremsstrahlung effect if the radiation density is high enough. Detailed calculations of the cross sections as a function of energy, angle and field strength in a thermal plasma have been given by Bussard *et. al.*, (1986), including the effect of higher resonances in the relativistic case. The cross section behaves $\propto \omega^{-1}$ at frequencies below the resonance, starting at a value below the thermally broadened resonance peak.

4. SPECTRAL EFFECTS IN ACCRETING X-RAY PULSARS

Accreting pulsars make up a large fraction of all known galactic X-ray sources, several dozen having been measured. The spectra are typically hard, often a power-law extending up to a maximum energy $E_m \simeq 20-50$ keV followed by a dropoff at higher energies. The pulse shapes, believed to be caused by magnetic beaming, are energy dependent. Lines at around 6.5-7 keV have been measured in a number of them (White, Swank and Holt, 1982), but these are believed to be K_α fluorescence lines of Fe in lower ionization stages ($< Fe^{18+}$), which would arise far from the surface of the star (since no gravitational redshift is seen), possibly in the Alfvén surface or the wind from the companion. No magnetically shifted atomic or ionic lines have been positively identified thus far. On the other hand, cyclotron lines have been reported in two of them, Her X-1 (Trümper *et. al.*, 1978) and 4U0115+63 (Wheaton *et. al.*, 1979, White *et. al.*, 1982), indicating field strengths B_{12} of about 3.3 and 1.1 respectively. Radiative transfer calculations in the coherent scattering limit (neglecting comptonization) allow one to calculate energy dependent pulse shapes at energies below the resonance from simple emission regions ,e.g. caps or columns, c.f. Kanno, 1980, Nagel, 1981a, Kaminker *et. al.*, 1982, 1983. Since the pulse (or beam) shapes depend on the ratio of the frequency to the cyclotron frequency, it is possible to attempt to infer the field strength in other sources where cyclotron lines are not seen, e.g. Kanno, 1980, Mészáros, 1982, Kii *et. al.*, 1986. The energy and strength of the cyclotron features are pulse phase dependent (Pravdo *et. al.*, 1979, Voges *et. al.*, 1983), an effect which is understandable in terms of the angle dependence of the Doppler shifting of the resonance and the angle dependence of the continuum and line flux caused by the magnetic angle and frequency dependence of the opacities. To properly model this one needs to include Comptonization as well as angular effects in the radiative transfer, c.f. Mészáros and Nagel (1985a,b). Using flat space propagation (i.e. neglecting general relativistic effects such as light bending), this model comparison indicates that the Her X-1 radiation is of a pencil beam type, in order to reproduce the observed decrease of line energy with increasing phase. Other indications favoring a pencil beaming pattern at some distance from the neutron star have been put forward by Trümper *et. al.*, 1986, based on the multiple peak structure of Her X-1. Interestingly, from simplified radiation hydrodynamic calculations (Basko and Sunyaev, 1976, Wang and Frank, 1981) one might conclude that higher luminosity pulsars such as Her X-1 ($L_x \gtrsim 0.1 L_{Ed}$) would have a radiation deceleration shock, and therefore an accretion column, rather than a low profile cap, a configuration which would naively lead to a fan-beaming pattern. More detailed radiation hydrodynamic calculations including magnetic anisotropies and resonance effects are needed to confirm this, c.f. Klein *et. al.*, 1985. However, if it proves that close to the star the radiation is emitted sideways (fan), gravitational light bending can distort this into a pencil beam at $R \gtrsim few R_*$, if the neutron star is more compact than about 2-2.2 Schwarzschild radii, c.f. Mészáros and Riffert, 1988. This would also reproduce the observed pulse phase dependence of the cyclotron line energy observed, and reconcile the expected presence of a stand-out column with an effectively observed pencil beam at large distances.

One of the best tools for investigating the geometry of the emission regions of compact objects is X-ray polarimetry, which can probe the directionality and the type of physical radiation mechanism of a variety of sources where imaging is impossible due to the small scales involved (Rees, 1975). This is particularly true for strongly magnetized X-ray sources, where the emission and transfer processes are strongly polarization dependent (Gnedin and Sunyaev, 1974) and a number of relevant calculations and estimates have been presented by Mészáros,*et. al.*(1988). In accreting pulsars, the degree of linear polarization obtained from simple accretion columns and polar caps can get up to 70-80 % near the cyclotron energy, and is very large also in the continuum, being a strong function of the pulse phase. It is possible to distinguish between pencil and fan beam radiation patterns because of the different correlation between flux and polarization degree maxima as a function of phase. Rocket borne detectors with current design scattering polarimeters (Novick *et. al.*, 1985) could measure polarizations down to 2 % in Her X-1 in about $2\ 10^5\ s$, while instruments on board a space platform with a photon collector could achieve similar sensitivities in extragalactic sources. This would be decisive for determining whether the emission mechanism of AGNs is indeed non-thermal (e.g. inverse synchro-Compton) or quasi-thermal (e.g. a thick accretion disk), since these alternatives have drastically different polarization predictions. It would also provide invaluable information about the magnetic field direction and/or the emission region geometry.

5. MAGNETIC SPECTRAL EFFECTS IN GAMMA-RAY BURSTERS

The evidence for Gamma-ray bursters (GRBs) being magnetized neutron stars is strongly suggestive, although not universally accepted. The partial similarity in temporal behavior to X-ray bursters, the presence of pulsations in at least one object (GRB 030579) and the observation of low energy (30-60 keV) cyclotron-like features in about a third of the GRBs detected with KONUS (Mazets *et. al.*, 1981) argue for this, as well as the fact that a magnetic field might be better in explaining why γ-rays and not X-rays are observed (smaller effective area, lack of thermal equilibrium over the short time of the burst, etc.), c.f. Liang, 1982, Woosley, 1984. Cyclotron lines have been also reported from SMM in one object (Dennis *et. al.*, 1982), and most recently from TENMA in two cases (Murakami *et. al.*, 1988). However the interpretation is complicated due to the lack of significant X-ray emission, and the apparent small upper limits ($B_{12} \lesssim 0.2 - 0.4$) on field strength inferred (Matz *et. al.*, 1985) from SMM burst statistics at 1-10 MeV, based on the expected effectiveness of the magnetic one-photon pair creation in a field of the magnitude indicated by the low energy line features. This prompted a reevaluation of the magnitude of the field and the location of the emission in simple models (Zdziarski, 1987, Lamb, 1988), and led to the investigation of more involved or alternative models. Spectral models based on synchrotron emission were most recently calculated by Brainerd and Lamb, 1987, and Brainerd, 1988.

The problem of γ-ray propagation in a relativistic magnetosphere with an arbitrary dipole field has been recently considered by Riffert, Mészáros and Bagoly (1988). Interesting features arise from the angle and frequency dependence of the absorption threshold ($\omega_t > 2mc^2/sin\theta$) and the fact that the photon paths bend in the gravitational field, as well as being redshifted. The magnitude of the bending of course depends on the compactness of the neutron star. The escaping beams of high energy radiation are broader for compact neutron stars, and for smaller fields. However, at a given field, even a moderately compact star gives a significantly broader escape beam than inferred from simple flat space calculations. Furthermore, as one increases the field beyond about $B_{12} \simeq 0.25$, the beam shapes saturate, no longer narrowing as one increases further the field strength, this saturation effect arising simply from the double exponential nature of the angle dependent transport problem (the escape is proportional to $e^{-\tau}$ and the cross section is also exponential in θ, ω). A theoretical simulation of the expected SMM statistics (Mészáros, Bagoly and Riffert, 1988) indicates that if one assumes that all stars sampled have the same magnetic field, then this field indeed should be less than about $B_{12} \lesssim 0.4$, in agreement with Matz *et. al.*, 1985. However, it is more likely that one is sampling a distribution of field strengths, if for no other reason that the latter may decay in time. If one has a combination of low field and high field objects, then due to the saturation effect mentioned above, the sample could be hiding a considerable fraction of rather large field objects, since their beam sizes are not correspondingly narrower. A simulation of expected SMM statistics in this case indicates that the SMM and KONUS statistics can be compatible with each other, with a considerable ($\gtrsim 1/3$) fraction of neutron stars having fields $B_{12} \gtrsim 5$. In this case, an understanding of the low energy spectrum involving cyclotron lines will require further work.

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DISCUSSION-P. Meszaros

G. Bisnovatyi-Kogan: Neutron star radius depends on the equation of state. Will your conclusion about the possibility of large magnetic field in gamma-ray bursts due to gamma-ray effects survive for large neutron star radius?

P. Meszaros: For $R \sim < 5\ R_{schwarschild}$ we get a poorer fit to the SMM detection rates. Smaller radii, between 2 and 2.5, provide better fits.

J. Krolik: Did you consider the effects of two possibly important complications, the effects of the radiation field in populating the higher harmonics, and the magnetic effects in changing the radiation pressure entering estimates of when a radiation shock appears?

P. Meszaros;: We are currently in the process of addressing the first question with Steve Alexander. The second problem requires a careful numerical treatment of the radiation hydrodynamics with magnetic opacities, on which Klein, Arons and Lea are currently working.

N. Itoh: You assumed an exponential decay of neutron star magnetic fields in your model of γ-ray bursts. What kind of timescale did you take for the exponential decay?

P. Meszaros: We did not use a specific decay law. That one as an example. The important thing is that we are likely to be sampling neutron stars with a variety of field strengths.