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High Energy Emissions from Young Stellar Objects

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Abstract. X-ray emissions from Young Stellar Objects (YSO) are detected by many X-ray missions that are providing important information about their properties. However, their emission processes are not fully understood. In this research note, we propose a model for the generation of emissions from a YSO on the basis of a simple interaction between the YSO and its surrounding circumstellar accretion disc containing neutral gas and charged dust. It is assumed that the YSO has a weak dipole type magnetic field and its field lines are threaded into the circumstellar disc. Considering the motion of ions and charged dust particles in the presence of neutral gas, we show that the sheared dust-neutral gas velocities can lead to a current along the direction of ambient magnetic field. Magnitude of this current can become large and is capable of generating an electric field along the magnetic field lines. It is shown how the particles can gain energy up to MeV range and above, which can produce high-energy radiations from the YSO.

Key words. Accretion discs—dusty plasma—high energy emission—stars.

1. Introduction

X-ray emissions from YSOs are detected by X-ray missions like *Einstein X-ray Observatory* (1978–1982), *ROSAT* (1990–1999), *Chandra* (1999–), *XMM-Newton* (1999–), etc (Feigelson and De Campli 1981; Neuhauser 1997; Giardino *et al.* 2007). They have become a routine tool for the study of star forming regions. The number of known X-ray emitting YSOs has increased considerably after the observations of ROSAT Observatory. The important result from ROSAT has been the detection of X-ray emissions from Class-I protostars (already having an accretion disc and still supplied with a relatively massive circumstellar envelope). X-ray emission from these sources seems to be a common feature (Ozawa *et al.* 2005). It is an universal feature in Class-II sources (young stars actively accreting from a circumstellar disc, but without a circumstellar envelope) and also in the more evolved Class III sources that are no longer accreting (Flaccomio *et al.* 2003; Preibisch *et al.* 2005). Thus the X-ray emissions seem to get generated in all evolutionary stages of YSOs.

High energy processes and X-ray emissions in young stellar objects are reviewed in Shu *et al.* (1997) and Feigelson & Montmerle (1999).

Several mechanisms have been proposed to explain these X-ray emissions. Early studies based on *ROSAT* and *Einstein* observations proposed a standard wind-shock model (Damiani *et al.* 1994; Zinnecker & Preibisch 1994). Other mechanisms proposed to attribute the emission to the magnetic activity related to coronal activity (as in late-type stars), star–disc interaction or late-type companions (Hamaguchi *et al.* 2005; Skinner & Yamauchi 1996; Skinner *et al.* 2004; Stelzer *et al.* 2006). An emission mechanism was proposed in several sources from shocks in accreting plasma (Kastner *et al.* 2002; Stelzer & Schmitt 2004; Schmitt *et al.* 2005; Gunther *et al.* 2006; Argiroffi *et al.* 2007). It is expected that different proposed X-ray emission mechanisms might not be mutually exclusive but might coexist (Schmitt *et al.* 2005; Günther *et al.* 2006; Argiroffi *et al.* 2007).

The rotating cloud in the form of a disc around an YSO is believed to play an important role in generating intense radiation, bipolar flows, stellar winds and many other interesting phenomena (Begelman *et al.* 1984; Blandford and Pyne 1982). The accretion disc model for X-ray sources, quasars and active galactic nuclei has been studied extensively in the past (Blandford and Znajek 1977; Lubow *et al.* 1993). It is thought that accretion discs, whether in the star-forming region, X-ray binaries or at the center of active galactic nuclei are likely to be threaded by the magnetic field of the central object. Therefore, the role of magnetic field has been analysed in detail by a number of investigators for a compact object by considering ideal MHD (Lovelace *et al.* 1986; Mobarry and Lovelace 1986; Banerjee *et al.* 1995). In this note, we study the currents and magnetic fields as a result of the interaction of the newly born stellar object with the accretion disc around it. It is assumed that the dipole magnetic field of the central object is threaded into the disc, which is composed of ions, neutrals and charged dust particles. This is shown schematically in Fig. 1.

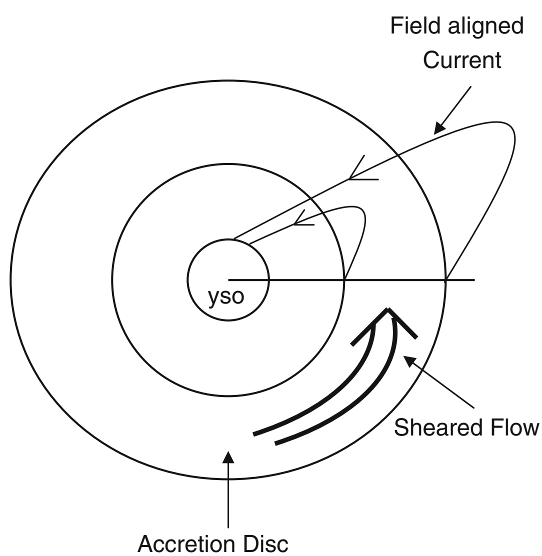

Figure 1. A simple model of YSO where magnetic field lines are threaded into the accretion disc. Sheared flow is shown by an arrow.

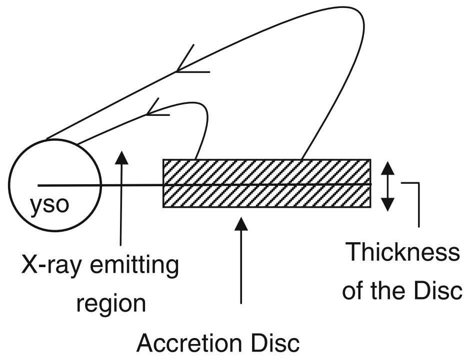

Figure 2. Thickness of the accretion disc is shown by the shaded area.

Actual interaction of the dipole field with the disc can be quite complicated. However, in a simple model, charged particles are tied to the magnetic field and thus co-rotate while neutrals are under the influence of gravity and move with Keplerian velocity in the disc. Even in the case of a non-rotating compact object, the motion of plasma is not Keplerian (Banerjee *et al.* 1995). In the magnetosphere of YSOs, the co-rotation is slower than the Keplerian velocity. Due to the strong coupling of dust with neutrals, neutrals are forced to co-rotate and produce shear in the velocity. Thickness of the accretion disc is schematically shown in Fig. 2.

We plan to study the effect of this shear in production of current along the magnetic field that is threaded in the disc. We do not use the ideal MHD and obtain electric field from the momentum equation. The governing equations are formulated in section 2. In section 3, the numerical estimates of the currents and electric fields are obtained. Gain in energy of the particles due to this process is discussed and some conclusions are drawn in section 4.

2. The basic equations

It is assumed that the disc is composed of partially ionized dusty plasma and therefore usual equations of continuity and momentum transfer for different species will be adequate to describe their motion. Quasi-neutrality is assumed and collisions of electrons with ions and neutrals are neglected. Dust particles are assumed to have uniform and constant negative charges. Dust charges are usually fluctuating, but this is neglected both for simplicity and for long time-scales considered for this study (Birk *et al.* 1996). Following Birk *et al.* (1998), we use the following set of basic equations:

$$(\partial\rho_a/\partial t) + \nabla\cdot(\rho_a v_a) = 0, \tag{1}$$

where the subscript denotes different species with ρ and v represents the usual density and velocity, respectively. The inertial forces for ions are assumed to be small and thus the momentum equation for ions is given by

$$0 = n_{\mathrm{i}}e\,(E + v_{\mathrm{i}} \times B/c) - \nabla p_{\mathrm{i}} - \rho_{\mathrm{i}}\,\nu_{\mathrm{id}}\,(v_{\mathrm{i}} - v_{\mathrm{d}}) - \rho_{\mathrm{i}}\,\nu_{\mathrm{in}}\,(v_{\mathrm{i}} - v_{\mathrm{n}}), \tag{2}$$

where i, d and n represent ion, dust and neutral components respectively.

Equations of motion for dust and neutrals are given by

$$\rho_d(dv_d/dt) = -n_d z_d e(E + V_d \times B/c) - \nabla p_d - \rho_d \nu_{di}(V_d - V_i) + \rho_d g - \rho_d \nu_{dn}(V_d - V_n), \quad (3)$$

and

$$\rho_n(dv_n/dt) = -\nabla p_n + \rho_n g - \rho_n \nu_{ni}(V_n - V_i) - \rho_n \nu_{nd}(V_n - V_d), \quad (4)$$

with the set of Maxwell's equations

$$\nabla \times B = 4\pi j/c = (4\pi e/c)(n_i V_i - n_e V_e - n_d z_d V_d) \quad (5)$$

and

$$\partial B/\partial t = -c\nabla \times E. \quad (6)$$

2.1 *Field aligned currents*

The general procedure to obtain the field aligned current is given below. Adding (2) and (3), the equation of motion of dust fluid is derived in the following form:

$$\rho_d(dV_d/dt) = -j \times B/c - \nabla p + \rho_d g - \rho_i \nu_{in}(V_i - V_n) - \rho_d \nu_{dn}(V_d - V_n), \quad (7)$$

where $j = e(n_i v_i - n_d z_d v_d)$, in which the electron contribution is neglected because of the depletion of electron density. Furthermore, we have assumed that $n_i e = n_d z_d e$ (charge neutrality), $p = p_i + p_d$ and $\rho_i \nu_{id} = \rho_d \nu_{di}$.

Taking a cross product of (7) with B, the perpendicular current $j_\perp$ can be obtained as

$$\begin{aligned} j_\perp &= (c\rho_d/B^2)B \times (dV_d/dt) + c(B \times \nabla p)/B^2 - \rho_d c(B \times g)/B^2 \\ &\quad + \rho_i \nu_{in}(c/B^2)B \times (V_i - V_n) + \rho_d \nu_{dn}(c/B^2)B \times (V_d - V_n) \\ &= J_{ina} + J_d + j_g + J_{in} + J_{dn}, \end{aligned} \quad (8)$$

where J_{ina} = inertia current = $(c\rho_d/B^2)B \times (dV_d/dt)$, J_d = diamagnetic current = $c(B \times \nabla p/B^2)$, J_g = current associated with gravity = $\rho_d c(B \times g)/B^2$, J_{in} = current associated with ion-neutral collisions = $\rho_i \nu_{in}(c/B^2)B \times (V_i - V_n)$, and J_{dn} = current associated with dust-neutral collisions = $\rho_d \nu_{dn}(c/B^2)B \times (V_d - V_n)$.

Using $\nabla \times B = (4\pi/c)J$, i.e., $\nabla \cdot J = 0$, the current density along the direction of the magnetic field line is given by

$$\begin{aligned} B(\partial/\partial s)(j_{||}/B) &= (2c\rho_d/B^3)\nabla B \cdot B \times (dV_d/dt) + (c/B^2)B \cdot \nabla \times \rho(dV_d/dt) \\ &\quad + (2c/B^3)\nabla B \cdot (B \times \nabla p) + (2c\rho_i \nu_{in}/B^3)(V_i - V_n) \cdot \nabla B \times B \\ &\quad + (c\rho_i \nu_{in}/B^2)B \cdot \nabla \times (V_i - V_n) + (2c\rho_d \nu_{dn}/B^3)(V_d - V_n) \cdot \nabla B \times B \\ &\quad + (c\rho_d \nu_{dn} B \cdot \nabla \times (V_d - V_n)/B^2) \ . \end{aligned} \quad (9)$$

The terms containing ∇B in the above equation are seen to be small compared to the remaining terms and thus the equation reduces to the following:

$$\begin{aligned} B(\partial/\partial s)(j_{||}/B) &= cB \cdot (\nabla \times \rho_d(dV_d/dt))/B^2 + (c\rho_i \nu_{in}/B^2)B \cdot \nabla \times (V_i - V_n) \\ &\quad + (c\rho_d \nu_{dn}/B^2)B \cdot \nabla \times (V_d - V_n). \end{aligned}$$

It is possible to eliminate V_i using equation (5) if the electron contribution is small and then it reduces to

$$B(\partial/\partial s)(j_{||}/B) = cB\cdot(\nabla\times\rho_{\rm d}({\rm d}V_{\rm d}/{\rm d}t))/B^2 + (c^2\rho_{\rm i}\nu_{\rm in})/(4\pi n_{\rm i}e^2B^2)\nabla^2(B^2) + c(\rho_{\rm i}\nu_{\rm in}+\rho_{\rm d}\nu_{\rm dn})(B\cdot\nabla\times(V_{\rm d}-V_{\rm n})/B^2). \qquad (10)$$

As the acceleration and diffusion terms are small, the current will be generated mostly by the shear of the relative velocity of dust and neutrals. It can be represented by

$$B(\partial/\partial s)(j_{||}/B) \approx c(\rho_{\rm i}\nu_{\rm in}+\rho_{\rm d}\nu_{\rm dn})(B\cdot\nabla\times(V_{\rm d}-V_{\rm n})/B^2). \qquad (11)$$

3. Numerical estimates

3.1 *Current density*

It is assumed that the dust neutral velocity is given by the free fall velocity $= \sqrt{(2GM_{\odot}/10\ \text{AU})}$ (Birk *et al.* 1998), where G is the gravitation constant, $M_{\odot}$ is the mass of the star ($= 1.9\times10^{33}$ g) and a distance of 10 AU from the center is taken for free fall distance (1 AU $= 1.5\times10^{13}$ cm). The velocity is then estimated as $V\approx1.3\times10^6$ cm/s.

Now $\nu_{\rm in} = 5\times10^{-15}\times n_{\rm n}\sqrt{KT/m_{\rm i}} = 10^3$/s, $\nu_{\rm dn} = 3.2\times10$/s, with $T_{\rm i}\approx T_{\rm d}\approx 700$ K, $n_{\rm i}/n_{\rm d}\approx10$, $m_{\rm d}\approx10^3 m_{\rm i}$, $n_{\rm n}\approx10^{12}$ cm^{-3} and $n_{\rm i}\approx10^{11}$ cm^{-3}. For L = shear length and $B = 1$ G, the field-aligned current from eq. (11) can be obtained and is given by $B(\partial j_{||}/\partial s)\approx2.6\times10^7/L$, and $j_{||}\approx2.6\times10^7\times(D/L)$, where D is the effective length along the field line with $D/L\approx10$, $j_{||}\approx2.6\times10^8$ stat amp/cm^2 $=10^4$ amp/m^2. This current is quite large and depends on the ratio *D/L*, which is an important variable.

It is now important to obtain the electric field along the magnetic field that will be capable of accelerating particles to a very high level of energy that can generate high energy emissions. Collisions between ions and neutrals, and ions and dust particles produce very high resistivity in the interacting region and produce electric field of high intensity which is derived in the following:

$$E_{||} = j_{||}/\sigma = (m_{\rm i}\nu_{\rm in})j_{||}/(Zn_{\rm i}e^2)\approx2\times10^{-5}\ \text{stat volt/cm}\approx0.6\ \text{volt/m}.$$

The magnetic field aligned potential structure ϕ is then given by $\phi = \int E_{||}{\rm d}s \approx 2\times10^{-5}$ stat volt/cm $\times D$, where D is the length of the magnetic field in the interaction region. It is assumed that the magnetic field line length in the interaction region (which is the extent of the accretion disc in the vertical direction) is about one-tenth of the radius of the stellar object. This is quite reasonable because the circumstellar disc may be thin and therefore the interaction region will not exceed the width of the disc. It is, however, possible to have a thick disc around the central object, which may be comparable to the radius of YSO and then the interaction region could be quite large (Banerjee *et al.* 1997). Consequently, the potential structure can become very large. For example, the thin disc approximation gives $\phi = 1.3\times10^4$ stat volt for $D = 6.7\times10^8$, and $\phi = 1.3\times10^5$ stat volt for $D = 6.7\times10^9$ cm.

3.2 *Energy gain by the particles*

The change in energy of the particle due to this electric field is given by

$$\langle \tfrac{1}{2} m v^2 \rangle = \int qE \mathrm{d}s \approx 9.6 \times 10^{-15} \times D,$$

where D is the length of the magnetic field in the interaction region and can be estimated as one-hundredth of the radius of YSO. Assuming that the YSO is as large as our Sun, this length could be about 6.7×10^8 cm (radius of the Sun is 6.9×10^{10} cm). Thus the change of energy $\langle \frac{1}{2} m v^2 \rangle = 9.6 \times 10^{-15} \times 6.7 \times 10^8$ erg, which is 6.3×10^{-6} erg or 6×10^6 eV. Thus, this process can accelerate the particles upto 6 MeV in principle or even more depending upon the extent of interaction region in the vertical direction.

4. Discussion and conclusions

From the mechanism described here, it is seen that both the charged particles, electrons and ions, are accelerated. When they move along the magnetic field and collide with the neutrals or ions near the surface of the YSO, X-rays are produced by different ways. Bombarding energetic electrons into the target species can eject electrons from the inner shell (K shell) of the atoms. This produces vacancies which is filled in by electrons from the higher levels emitting X-rays with frequencies determined by the difference between atomic energy levels of the target species. This can lead to substantial characteristic X-rays in the continuum spectrum emission of YSO, which is the result of thermal Bremsstrahlung.

Hard X-rays are largely generated by non-thermal Bremsstrahlung due to suprathermal electrons from a part of continuous spectrum of electrons including high energetic relativistic particles that can be generated by the mechanism described above. These X-rays can also be produced by inverse Compton emissions of extreme relativistic electrons. However, in our model, ions also play an important role. Ions are accelerated to very high energy. These can produce X-rays as they propagate along the magnetic field and precipitate into the atmosphere of YSO. In this case, X-ray emissions arise in the following manner. The energetic ions are nearly stripped of electrons while precipitating and they are either directly excited or charged exchanged into an excited state which emits an X-ray photon upon decay back to the ground state. This process seems to be effective in generating X-rays in planetary atmosphere, particularly X-ray emission from Jupiter, where accelerated ions from the magnetosphere propagate along the magnetic field into the auroral region (Bhardwaj and Gladstone 2000). This can probably be important for observed broadened iron emission line and CO emission line from protostars (Koyama *et al.* 1996).

X-rays can interact with the molecular cloud around the star including the outflows of YSO and can induce a variety of effects including ionization, heating and modification of dust grains composition. X-ray ionization of molecular gas around YSO plays an important role in coupling of gas and magnetic field. X-ray absorption also is an important process in studies of young stars. It produces secondary electrons due to interaction with the outflows and other materials. However, dust particles existing in the medium, subject to an X-ray will absorb most of the secondary electrons resulting in increased temperature and will obscure this part of the radiation.

It is difficult to give the typical size of the hotspot, or the X ray emitting source. However, X-rays appear to emit from the envelope formed by the magnetic field line connecting the high latitude region and the circumstellar disc. The emissions are observed to be emanating from a relatively large region of YSO, which indicates that the process of emissions is not probably restricted to the area near the surface of the object where nearly fully ionized plasma occurs. Furthermore, it is probably not restricted to the small interaction region that we have considered above. It may be worthwhile to consider that the magnetosphere around the YSO is filled with partially ionized dusty plasma. Then the resistivity arising due to collisional effect will exist along the field line to a considerable length up to the fully ionized region in addition to the interaction region. In this case the electric field will be along the total effective field line and produce a large field line potential structure.

The change in energy of the particle due to this electric field is then given by

$$\langle \tfrac{1}{2} m v^2 \rangle \sim \int q E_{||} \mathrm{d}s \sim 9.6 \times 10^{-15} \mathrm{erg} \times d,$$

where d is the length of total magnetic field line up to the region near the surface of YSO, and d may be estimated as twice the star radius, where the star radius can be about $\sim 6 \times 10^{10}$ cm (almost equal to the Sun's radius). The energy gain of the particle can then become in the order of 1 GeV. This gives the radiation at a very high energy level like hard X-ray or gamma rays. This is a possible consequence of the above magnetospheric model.

In all the calculations done in the above, we have considered the collisional resistivity. However, it is possible to generate many plasma instabilities due to field-aligned currents, which give rise to anomalous resistivity that may even be larger than collisional resistivity by an order of magnitude. As a result, electric field strength will be enhanced considerably and the potential will become larger than that described earlier. On the whole the particles gain more energy to generate emissions with sufficiently large energies.

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