

Effect of beam-plasma instabilities on accretion disk flares

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Abstract. We show that a certain class of flare models for variability from accretion disk coronae are subject to beam-plasma instabilities. These instabilities can prevent significant direct acceleration and greatly reduce the variable X-ray emission argued to arise via inverse Compton scattering involving relativistic electrons in beams and soft photons from the disk.

Key words: accretion, accretion disks – plasmas – Sun: flares – galaxies: active – X-rays: general

1. Introduction

The origin of fluctuations in the emission from Active Galactic Nuclei (AGN) and binary X-ray sources is an important and long-standing problem. One frequently considered possibility employs flares in the coronae around accretion disks to produce rapid energy release, particle acceleration and radiation (e.g., Galeev, Rosner & Vaiana 1979; Kuperus & Ionson 1985; for a review, see Kuijpers 1995). These models usually build upon our understanding of solar flare physics.

A particular model of this type has been proposed by de Vries & Kuijpers (1992; hereafter dVK), and was specifically applied by them to X-ray variability of AGNs. Their model is an elaboration on typical flare scenarios, in that, as usual, the source of energy is stored in magnetic fields in coronae of accretion disks. They estimate the power released in flares in a radiation pressure dominated corona, which they stress is a different environment from the gas pressure dominated solar corona. They argue this leads to a situation where beams of relativistic electrons are produced in the corona and then lose essentially all of their energy through inverse Compton scattering on UV disk photons before they can stream back to the disk. They further argue that these inverse Compton (IC) photons produce the X-ray variability seen in Seyfert galaxies, and are able to calculate spectral power-densities in reasonable agreement with observations.

However, the dVK model does not take into account other mechanisms that might vitiate some of their key assumptions. We note that dVK briefly argue that, particularly if radiation

pressure dominates the energy density in the corona, as is indeed likely around standard thin accretion disks (e.g., Shakura & Sunyaev 1973) which they assume, energy losses through scattering on plasma waves are unimportant; then the dominant losses will be to IC scattering. However, it is well known that an electron beam-plasma system is often susceptible to the excitation of beam-plasma instabilities which usually have large growth rates (Sturrock 1964). Here we argue that when these beam-plasma instabilities (BPIs) are taken into account, the rate of loss of energy by the electrons for the accretion disk coronae conditions suggested by dVK is typically much higher than the rate of gain of energy through direct acceleration by the electric fields, which are presumed to arise in reconnection events. Therefore beams of electrons usually will not reach the high Lorentz factors needed to produce most X-rays by the IC process. In many accretion disk models X-rays are usually produced through IC scattering of soft photons on hot thermal electrons (e.g. Shapiro et al. 1976; Liang & Price 1977). In such a situation beam-plasma instabilities are not excited, and only thermal spontaneously excited plasma waves should exist. These will have energy densities less than the thermal energy density of the plasma, which in turn is much less than the radiation energy density. In this case, the argument of dVK would be valid, but, once they assume a beam is present, then beam-plasma instability effects *must* be included.

2. Growth of beam-plasma instabilities

The key assumptions of the dVK model are that: 1) relaxation of magnetic structures efficiently produce relativistic electron beams; 2) the particle beam is a mono-energetic stream of electrons with an initial Lorentz factor γ_0 ; 3) the ambient radiation is from a quasi-infinite disk and can be considered as uniform and isotropic, with a radiation density u_{rad} ; 4) the beam is optically thin, so multiple scattering of photons can be ignored. Although (3) is an approximation, it is a reasonable one, and (4) is certainly plausible under many circumstances. But the core of their argument hinges on the ability of the neutral sheet in the reconnection process to quickly accelerate electrons via a direct electric field. During this acceleration process dVK claim

the equation for the acceleration of a single electron suffering IC losses is

$$\frac{d\gamma}{dt} = \chi_1 \frac{(\gamma^2 - 1)^{1/2}}{\gamma} - \chi_2(\gamma^2 - 1), \quad (1)$$

where, $\chi_1 = eE/m_e c$ and $\chi_2 = 4\sigma_T u_{rad}/3m_e c$, with all symbols having their usual meanings. In that the first (positive) term starts out substantially greater in magnitude than the second (negative) one, acceleration will ensue until a limiting Lorentz factor is reached when the two terms balance:

$$\gamma_\infty = 2^{-1/2} [1 + (1 + 4\chi_1^2/\chi_2^2)^{1/2}]^{1/2}. \quad (2)$$

The electric field is reasonably taken by dVK to be the Dreicer value, which we take as: $E_D = 6\pi n_p e^3 \ln\Lambda / (k_B T_e)$, where n_p is the electron density of the ambient plasma, $\ln\Lambda \approx 20$ is the Coulomb logarithm, and all other symbols have their usual meanings. With typical AGN values ($n_p \approx 10^{10} \text{ cm}^{-3}$, $T_e \approx 10^6 \text{ K}$, and $T_{rad} \approx 10^5 \text{ K}$) they find $\gamma_\infty \approx (\chi_1/\chi_2)^{1/2} \approx 30$. They then conclude that the electrons will all reach this terminal Lorentz factor before the acceleration terminates and the electrons then lose their energy against the disk photons providing the background radiation field.

We now show that since a BPI is excited, it will dominate the energy losses for the beam and actually prevent the electrons from reaching the high Lorentz factors calculated by dVK. Under these circumstances there will be very little IC radiation, so that, while a great deal of energy may be released through magnetic reconnection, the bulk of the energy will probably provide heating to the corona (e.g., Liang & Price 1977) but is unlikely to yield the bulk of the X-rays directly through IC emission.

The dominant growth rate of the BPI depends on the relative magnitudes of the bulk velocity of the beam, v_b , and the mean thermal velocity in the beam, v_{Tb} ; under some conditions, v_{Te} , the mean thermal velocity of the ambient electrons, also must be taken into account. The standard formula for the BPI growth rate, valid for $v_b > (n_p/n_b)^{1/3} v_{Tb}$, is our Case 1 (e.g., Mikhailovskii 1974)

$$\Gamma_{bp} = 0.7 \left(\frac{n_b}{n_p} \right)^{1/3} \omega_{pe}, \quad (3)$$

where n_b is the beam density, n_p is the ambient plasma density (here, in the disk corona), and $\omega_{pe} = 5.47 \times 10^4 n_e^{1/2}$ is the plasma frequency in terms of the ambient electron number density in cgs units. The frequency at which this mode grows is $\omega_{pe}(1 - 0.4(n_b/n_p)^{1/3})$.

If the beam starts out very slowly, with $v_b < (n_p/n_b)^{1/3} v_{Tb}$, then the ‘‘weak’’ version of the BPI is relevant, and this is our Case 2 (e.g., Benz 1993)

$$\Gamma_{bp,w} = \left(\frac{n_b}{2n_p} \right) \left(\frac{v_b}{v_{Te}} \right)^2 \omega_{pe}, \quad (4)$$

and the frequency at which this dominant mode is excited is ω_{pe} . Under the limited circumstances that $v_{Te} > v_b > v_{Tb}$, the ‘‘hot-electron’’ Case 3 yields (e.g., Mikhailovskii 1974),

$$\Gamma_{bp,he} = \left(\frac{n_b}{n_p} \right)^{1/2} \frac{v_{Te}}{v_b} \omega_{pe}, \quad (5)$$

where this dominant mode is at a frequency of $(v_b/v_{Te})\omega_{pe}$.

The AGN corona values of dVK for $n_p = 10^{10} \text{ cm}^{-3}$ and $T = 10^6 \text{ K}$, which we also believe are reasonable, will be adopted here. There are, however, additional parameters that must be considered now (basically in lieu of the radiation temperature, or u_{rad} , needed by dVK). First, $\zeta \equiv n_b/n_p$; for solar flares this value is $\sim 10^{-6} - 10^{-4}$ (Benz 1993); however, we will bear in mind the possibility that this ratio may be higher in this type of radiation dominated plasma. We also need initial values of v_b and v_{Tb} , to determine which of the three Cases defined above should be considered. For us to say that a beam actually exists we must always demand that $v_b > v_{Tb}$.

Note that the BPI directly gives the rate of growth of an electric field in the plasma, and the energy loss goes as the square of the field strength. Then we find that when the relativistic effects that arise if the Lorentz factors really could become large are included, the rate of change of energy of electrons in the beam is,

$$\frac{d\gamma}{dt} = \chi_1 \frac{(\gamma^2 - 1)^{1/2}}{\gamma} - 2\alpha\gamma\Gamma_{bp}(\gamma), \quad (6)$$

where $\alpha \equiv W/E = W/\gamma n_b m_e c^2$, is the ratio between the wave energy density, W , and the electron beam energy density, E . In order to determine W , knowledge of the saturation mechanisms of the wave field are needed. Often, in order to avoid a detailed discussion of the saturation mechanisms, which tend to operate in multiplicity in a plasma, the condition of equipartition of energy between the waves and the beam particles is used (Treumann & Baumjohann 1997). In that case α is approximated to unity, and we consider this situation first. Case 4, where $\alpha \ll 1$, and the saturation occurs earlier by trapping, will then be addressed.

In Eq. (6) we have ignored the IC term appearing in Eq. (1), having replaced it with a generic form of the BPI growth rate; the fact that the BPI term is much bigger than the χ_2 term for all reasonable circumstances will soon become evident. The dominant dependence of Γ_{bp} upon γ for the first three cases arises through the replacement: $n_b \rightarrow n_b/\gamma^3$ (e.g., Walsh 1980; Krishan 1999), which effectively modifies ζ , which is defined as the density ratio at non-relativistic relative velocities. In Cases (2) and (3) we must also write $v_b/c = (\gamma^2 - 1)^{1/2}/\gamma$.

Now, for Cases 1, 2 and 3, respectively, we have:

$$\frac{d\gamma}{dt} = \chi_1 \frac{(\gamma^2 - 1)^{1/2}}{\gamma} - 2A_1, \quad (7)$$

with $A_1 = 0.7\zeta^{1/3}\omega_{pe} \simeq 8 \times 10^7 \zeta_{-5}^{1/3} n_{e,10}^{1/2}$, where the common notation, $X_n = X/10^n$, has been employed so that the physical parameters will be of order unity;

$$\frac{d\gamma}{dt} = \chi_1 \frac{(\gamma^2 - 1)^{1/2}}{\gamma} - 2 \frac{(\gamma^2 - 1)}{\gamma^4} A_2, \quad (8)$$

with $A_2 = 0.5(c/v_{Tb})^2 \zeta \omega_{pe} \simeq 3 \times 10^8 \eta_b^{-2} \zeta_{-5} n_{e,10}^{1/2}$, where we have now defined $\eta_b \equiv v_{Tb}/c \sim 0.01$;

$$\frac{d\gamma}{dt} = \chi_1 \frac{(\gamma^2 - 1)^{1/2}}{\gamma} - \frac{2\gamma A_3}{(\gamma^3 - \gamma)^{1/2}}, \quad (9)$$

with $A_3 = \zeta^{1/2}(v_{Te}/c)\omega_{pe} \simeq 2 \times 10^5 \zeta_{-5}^{1/2} \eta_{e,-2} n_{e,10}^{1/2}$, where now, $\eta_e \equiv v_{Te}/c \sim 0.01$.

Under any of these situations we have $\chi_1 = 5.2 \times 10^1 n_{e,10} T_{e,6}^{-1}$ with our definition of E_D (which is slightly larger than that of dVK, thereby only strengthening our argument). For any plausible initial value of $\gamma \sim 1$ the different dependences of Eqs. (7–9) upon γ are not important. What is important is that $A_1, A_2, A_3 \gg \chi_1 \gg \chi_2$; i.e., the energy loss term arising from any form of the BPI completely dominates over the energy gain term from direct electric field acceleration.

We now consider Case 4, where equipartition is not established. Under these circumstances, the growth of the Langmuir waves for the fastest initial beam situation, Case 1, is arrested by the trapping of the beam electrons. In this case, the ratio α is eventually given by the saturated value (Melrose 1986; Krishan 1999), $\alpha = 9/2[n_b/(2n_p\gamma^3)]^{2/3}$, and it can be a rather small number that reduces the loss rate significantly. This gives a chance for the situation envisioned by dVK to occur. In addition, α initially can start out below the saturation value as it arises from thermal fluctuations, and thus it could allow an initial thermal runaway. The detailed spatial and temporal structure of the reconnection sites will determine if this initial acceleration can play a significant role.

In spite of these uncertainties, we can obtain a reasonable estimate of the influence of BPI in the situation where equipartition is not established. We again consider all three cases discussed above, but we now include electron trapping and assume α to take the saturation value. Here the competition between the IC losses represented by χ_2 and the BPI losses represented by the Melrose α has to be considered carefully.

The inverse Compton term increases with γ whereas the α factor modifying the BPI term decreases with γ . Thus demanding that the BPI term is smaller than the IC term fixes the minimum value of γ necessary to validate the dVK proposal. A detailed calculation yields the results for the three cases as follows: case (1a), $\gamma_{min} = 54$; case (2a), $\gamma_{min} = 21$; case (3a), $\gamma_{min} = 9.16$. Thus it is clear that only in case (3a), it is likely that the IC term dominates and hence the dVK proposal is valid. This requires rather special conditions for the flare models to work.

This type of runaway acceleration has been observed in the laboratory under specific circumstances which lead to a very weak beam plasma instability. In laboratory experiments, the runaway electrons are observed detached from the main body of the plasma, as for example in a stellarator. If the runaway electrons hit the tungsten aperture, they generate X-rays which can be detected. Provided the conditions are right, the runaway electrons undergo instabilities producing plasma oscillations which then couple to the ions. This principle is applied in the design of some electron tube oscillators (Rose & Clark 1961). Thus the runaway electrons can stably propagate under certain circumstances, but will be affected by a BPI if they do satisfy the conditions for it. These conditions are essentially on the velocity of the beam and its thermal spread, as we have already discussed for the first three cases above.

Often it is found that a regime of strong Langmuir waves is quickly reached and these waves are further subjected to modulational instabilities. Thus, different saturation mechanisms operate at different stages of the development of the instability, depending on beam plasma parameters. However, under the circumstances and parameters proposed by dVK, the damping is severe.

3. Discussion and conclusions

We thus conclude that the mechanism proposed by dVK should not generally work unless much greater densities are possible in the coronae at the same time that the temperatures are lower, since χ_1 rises faster with n_p than does any form of Γ_{bp} , and declines faster with temperature. While denser coronae should be available around the accretion disks in X-ray binaries, the ambient temperatures will also be a good deal higher, so we cannot suggest a physically interesting situation where the BPIs do not dominate. If one could somehow begin with very large γ values, then the growth rate of the beam-plasma instabilities are reduced. For Case 1 this does not help, and no solutions for large γ are possible; however, for Cases 2 and 3, the relativistic decreases in the BPI rates are so substantial that high asymptotic γ values are allowed. This is also true for Case 4, where the saturation reduces the effectiveness of the BPI; however, even then the BPI can prevent much acceleration unless the beam already starts with a substantial value of γ or has such a low density in comparison to the ambient medium that it could not carry significant power. Moreover, we see no way to achieve these initially high γ values: that is what the dVK mechanism was supposed to accomplish, but now appears to be incapable of achieving.

Filamentation, which could produce denser beam fragments, could play a role by raising ζ locally. If any analogy can be drawn with solar flares, then the presence of rapid irregularities within the Type 3 radio bursts strongly indicates that the flux tubes are filamentary during the acceleration phase (e.g., Vlahos & Raoult 1995). However, this possibility is still insufficient to salvage this mechanism for AGN coronae, since even with $\zeta \sim 1$ the ratios of $A_{1,2,3}/\chi_1 > 1$. In Case 4, where saturation is important in principle, the large value of ζ implies that $\alpha \sim 1$ too (for initial $\gamma \sim 1$) so the loss term still would dominate.

Nonetheless, even with much of the energy going into wave turbulence, as we have argued, significant IC emission can be possible. This is because (as pointed out by the referee) trapping and other nonlinear effects can roughly heat the electrons up to $kT_e \sim e\phi$, with ϕ the electrostatic amplitude of the waves. Since the energy gain term (the first on the RHS of Eq. [1]) is essentially a constant, these ‘thermalized/trapped’ electrons can attain nearly the same energy as in the dVK picture. However this energy will not be in the form of a beam, as argued by dVK, but rather, will be present in an isotropic distribution. Then the IC process still works, and one of the points made by dVK, that much of the energy is lost by IC hard X-rays instead of ‘soft’ X-rays from material evaporated from the disk, can remain valid, as

already noted at the end of Sect. 1. In order to see if the inverse Compton losses actually dominate, detailed computations of these effects should be undertaken under various circumstances.

It is well known that in the case of the solar corona, the directly accelerated beams should be thermalized within a very short time through BPI (e.g., Sturrock 1964). In the standard picture, this produces Langmuir waves which then manifest themselves as various types of radio bursts if non-linear effects or transport from faster to slower electrons within the beam could dominate (e.g., Vlahos & Raoult 1995). However, energetic electrons have been observed in satellite measurements in near-earth orbit, and the outstanding question of the maintenance of these beams through their propagation from the sun to the earth has given rise to more complex models involving complex profiles of the electron beams (Vlahos & Raoult 1995). Instead of producing X-ray flares via a primary process as proposed by dVK, these secondary processes involving energy input to the plasma could contribute to variability in the radio band.

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