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MAGNETIZED HOT PLASMAS AT THE GALACTIC CENTER: FROM INTERMEDIATE TO SMALL SCALE X-RAY EMISSION

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Abstract. The Galactic center is known as a strong X-ray emission region. Here we present an overview of the X-ray properties and investigate two heating mechanisms that may play a significant role at intermediate and small scales. In a region of 300 pc size, the emission seems to originate in a diffuse hot ($k_B T$=7 keV) plasma. We present recent work on the confinement and heating of such a plasma, taking into account the peculiar properties of the central region. When getting to the scale of the central accretion disk, the emission becomes harder. Synchrotron-self Compton radiation originating in a gas of relativistic electrons ($\gamma \approx 10^2 - 10^3$) has been observed during flaring events. Such high energy particles imply efficient acceleration mechanisms. We present an acceleration process based on a large scale resonance and we discuss its efficiency.

1 Diffuse X-ray emission from the central molecular zone

As can be observed at all wavelengths, the Galactic Center (GC) region is a very particular region. The X-ray emission is much stronger than in the rest of the Galactic ridge. Infrared observations show that the GC corresponds to a strong concentration of cold molecular gas. At a radius of about 150 pc, the mean density jumps by a factor of 20 from outside to inside. All this cold molecular content is condensed in clouds and forms the so-called *Central Molecular Zone* (Morris & Serabyn 1996; Oka et al. 2001) that well matches the central X-ray emitting region. At radio wavelengths, observations also show numerous non thermal filaments that are observed nowhere else in the Galaxy (LaRosa et al. 2000). These filaments are beautifully aligned with the direction perpendicular to the galactic plane and suggest a strong, vertical magnetic field (Morris & Serabyn 1996). All these unique features probably result from the same global galactic dynamics and may contribute to make the situation at the GC very different from that farther out in the Galaxy.

For two decades, X-ray observations with *Einstein, HEAO, Ginga, ASCA*, and now *XMM-Newton* and *Chandra* have reported a diffuse emission from the Galactic ridge. This emission extends out to more than 4 kpc in radius (25° with a 8 kpc sun-Galactic center distance) from the central super massive black hole Sgr A*, but in the 1-10 keV band, it is very peaked in the first 2° (250 pc) at the Galactic center. The typical spectrum from this central region results from the contribution from several phases (Muno et al. 2004; Koyama et al. 2007).

1- Many K-α and K-β lines of very ionized metals (Si, S, Ar, and Ca) are observed in the 1-4 keV band. Those lines have been attributed to the soft ($k_B T \sim 0.8$ keV) plasma of young supernova remnants.

2- A fluorescence iron line at 6.4 keV, resulting from the interaction of cosmic rays with cold gas ($k_b T \sim$50 K) is also present.

3- Two iron lines at 6.7 and 6.9 keV are also observed. These lines correspond to very ionized states of Fe and therefore cannot originate in the soft phase.

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The diffuse emission is mainly characterized by these iron lines and by the underlying continuum. Two main ideas have been suggested to account for these lines. a) They originate in the hot plasma of many unresolved discrete point sources (mostly CVs). b) They originate in a hot ($k_BT \sim 7$ keV), truly diffuse plasma that bathes the emitting region.

The typical spectrum is very similar to that of sources such as Cataclysmic Variables, but so far only a fraction of the total X-ray emission in the 1-10 keV band has been resolved. To account for undetected sources, Log(N)-Log(S) diagrams can be built and extrapolated to weak sources. This work is subject to possibly large biases and uncertainties. Source confusion can also limit the detection capabilities of instruments, especially at high energy. Recent deep observations combined with new estimates of the unresolved population seem to show that the fraction of discrete point sources could be large in the Galactic ridge (Revnivtsev et al. 2006). The idea of a diffuse plasma was early suggested since the fits with such a thermal plasma match best the spectrum, but it was also very debated since it raises severe paradoxes. The temperature of this plasma is so high that it should not be confined by the gravitational potential, and the power required to heat it before it leaves the Galactic plane exceeds any known energy source. Also, even if the plasma is confined, no heating mechanism has been identified.

However, new observations with Suzaku have put a new light on these issues. They have shown that the remaining diffuse emission has not the same profile as the point sources in the first fractions of degrees at the Galactic center (Koyama et al. 2007). This points to a truly diffuse origin and it implies that the contribution of the diffuse plasma/discrete point sources is different at the Galactic center from in the Galactic ridge. Here we focus on this very central region and we present results on the modeling of a truly hot plasma that solve the paradoxes of its confinement and heating.

1.0.1 Plasma confinement

The idea that a diffuse 7 keV plasma should escape from the Galactic plane directly results from the (mono-) fluid assumption: the global sound speed of the plasma is larger than the escape velocity required for bodies to leave the gravitational well. This indeed could imply that the whole plasma must escape if it were composed only by protons or if all constituting species had the same behavior.

However, the plasma is composed by many species (electrons, protons, He ions and other heavy ions) and, on the typical escape time ($\tau_{\rm esc} \sim 5 \times 10^4$ yr), the plasma is not collisional ($\tau_{\rm coll} \approx 10^5$ yr). This basically means that the different species can have different behaviors and must be studied separately. Such an analysis is very similar to that in planetary atmospheres (except that the gas is a ionized plasma) and the results are comparable. Namely, by comparing the effective thermal velocity of an ion and its electrons ($v_{\rm th} = \sqrt{\frac{k_BT}{\mu m_p}}$, where μ is a mean molecular weight) with the escape velocity ($v_{\rm esc} \approx$1200 km/s), it is found that:

- The thermal velocity of protons ($v_{\rm th} \approx$1300 km/s) is larger than the escape velocity. At this hot temperature, protons are too light to be confined by gravity. This is basically the same result as the fluid one.
- The thermal velocities of heavier ions ($v_{\rm th} < 750$ km/s) are smaller than the escape velocity. Even with this high temperature, any ion other than a proton is heavy enough to be confined by gravity

As a consequence, the Galactic center can undergo a selective evaporation that naturally leads to the formation of a heavy, He-dominated plasma, that is confined by the Galactic potential in this region (Belmont et al. 2005).

1.0.2 Plasma heating

If there is no other cooling mechanism, such a bound plasma only cools by radiation, which is much more reasonable since the total X-ray luminosity of the central region is only $L \approx 4 \times 10^{37} erg/s$. Such a power can actually be balanced by viscous heating. The numerous molecular clouds that flow in the central region represent a large reservoir of kinetic and gravitational energy that can be dissipated by the viscosity of the diffuse plasma.

Because of its high temperature, the diffuse plasma is highly viscous ($\nu \propto T^{5/2}$, (Spitzer 1962)). However, the strong magnetic field inhibits the usual shear viscosity, only leaving the other component: the so called bulk viscosity related to the compression of the fluid. As the clouds motion is rather slow (subsonic), the associated compression is weak, which limits the dissipation efficiency. The overall dissipation depends on the exact wake of the clouds.

The wake of conducting bodies in a magnetized plasma has been studied in space science to investigate the motion of satellites in space magnetospheres. In first approximation, it is dominated by Alfvén perturbations that propagate along the field lines. These Alfvén waves forms a wing structure and carry a strong energy flux away from the cloud (Drell et al. 1965; Neubauer 1980). This flux depends on the magnetic field strength and for any value in the expected range (10μG-1mG), the cumulative flux associated to the motion of all the clouds in the central region is much larger that the X-ray luminosity. Only a fraction of this power is required to heat the diffuse plasma. To first order, Alfvén wave cannot be dissipated by the bulk viscosity since they are not compressible. However, it has been shown that non linear effects or a significant curvature of the field line ($R_c \sim$ 100 pc) provide sufficient dissipation to account for the hot plasma temperature (Belmont & Tagger 2006).

2 X-ray flares from the central black-hole

The view of the Galactic center at smaller scale is different. Contrary to the quiet central molecular zone, the sub-parsec scale region is strongly variable.

*2.1 The flow pattern around Sgr A**

It is now accepted that the compact radio source Sgr A* is the radiative manifestation of a supermassive black hole of mass $M = 3.6 \times 10^6 M_o$, with a Schwarzschild radius of 10^{12}cm. From radio observations, it was early suggested that this emission originates in a magnetized Keplerian flow within the inner few tens Schwarzschild radii. This is now supported by many observations from infrared to X-rays. Near-infrared (NIR) observations have shown that the counterpart is highly variable at these wavelengths (Genzel et al. 2003; Ghez et al. 2004). Since then, many flares (where the emission can jump by one order of magnitude) have been studied by photometry, spectroscopy and polarimetry (Eckart et al. 2006a,b). They appear at a rate of a few per day and last for about 1-3 hours. More recently, a similar variability has been observed in X-ray wavelength and it was shown that the X-ray flares are correlated with the strongest IR flares, pointing to a common physical origin (Bélanger et al. 2005). Several flares also displayed quasi-periodic modulations with a period of about 20 min that seems to decrease with time. This was interpreted as a wave pattern or a hot spot spiraling down to the last stable orbit (Bélanger et al. 2006).

All these observations point to a picture where a Keplerian accretion disk surrounds the black hole and undergoes violent accretion events responsible for the observed flares. Such a disk is probably quite different from standard accretion disks in X-ray binaries. It may be thicker and numerical simulations have shown that the average angular momentum of gas captured by the black hole (mostly stellar winds) is too small for a large disk to form. On the contrary, clumps of wind material only circularize at typically $10 - 10^3$ Schwarzschild radii. The structure of the magnetic field in this accretion disk is uncertain. From observations of a large scale structured vertical magnetic field in the larger central molecular zone and from comparisons with disks of X-ray binaries, we will assume that the accretion disk around Sgr A* is threaded by a large scale vertical field. In this situation, it has been shown that a strong instability can develop within the disk: the magnetic Rossby Wave Instability (RWI, Tagger & Melia 2006). It appears as a spiral density wave that destabilizes the Keplerian flow and leads to violent accretion events that last typically a couple of hours and produces strong bursts. In addition, the rotating spiral wave can generate the QPOs observed in some flares. Here we assume that the photometric properties of the flares are produced by the magnetic RWI and we investigate their spectroscopic properties in this context.

2.2 Magnetic pumping

It is believed that the flare emission is synchrotron-self compton radiation. High energy electrons produce the mid-IR emission by synchrotron radiation and then comptonize these soft photons to X-ray energy. In order to fit the spectra, relativistic electrons with Lorentz factors of $\gamma \sim 10^2 - 10^3$ are required (Liu et al. 2006b; Eckart et al. 2006a). A scenario in which a fraction of the gravitational energy of the flow is transferred to a population of non thermal electrons is favored. Two mechanisms have been proposed so far to account for this transient acceleration. Reconnection was suggested to heat the electrons (Trippe et al. 2007), but the authors do not give any estimate. Only little is known about reconnection and there is no guaranty that the required conditions are satisfied and that a reconnection rate efficient enough can be sustained. Also, stochastic accelaration by *transit-time damping* with plasma waves can occur if the turbulent conditions are satisfied, that is if there is a well developed small scale turbulence (Liu et al. 2006a,b).

Here we investigate how the same *transit time-damping* mechanism (also called *magnetic pumping*) could extract energy, not from the small scale turbulence, but directly from large scale modes of the accretion disk. In this case, the acceleration results from the resonance of two frequencies:

1. In a structured magnetic field, electrons move freely along the field lines and diffuse only very slowly across them. At high energy, Coulomb collisions are rare and assuming that the turbulence has not developed to a strong level, electrons can be considered as balistic particles moving along the field lines in the gravitational potential. Namely, they oscillate vertically with a frequency that is a fraction of the Keplerian one, depending on the energy and the nature of the particles (ion/electron).
2. The magnetic RWI produces a strong magnetic perturbation that extends above the disks. As the spiral wave rotates in the disk, the corresponding perturbed Lorentz force is periodic. Since the gravity is the main driver of the the instability, the spiral wave also has a frequency close to the Keplerian one.

At a given radius, the frequency of part of the particles turns out to be comparable with the Keplerian one, and thus to that of the spiral-Rossby pattern. These particles are resonant and gain energy. The corresponding theory was developed in the context of X-ray binaries (Belmont & Tagger 2005) and it is found that the typical acceleration time is:

$$\tau_{\rm acc} \approx \tau_K \left(\frac{b}{B_0}\right)^{-2} \left(\frac{\omega_c}{\omega_K}\right)^{-1} \tag{2.1}$$

where τ_K is the reference Keplerian dynamical time, b/B_0 is the amplitude of the magnetic perturbation, and ω_c is the resonant frequency.

In X-ray binaries, this mechanism was found to be very inefficient for several reasons. First, electrons oscillate too fast and only protons can be resonant, so that a secondary energy transfer from protons to electrons is required to produce the observed emission. Second, the wave amplitude is weak (~ 0.2). And last, the dominant cooling mechanism (Compton cooling) is drastically efficient (the acceleration time is typically two orders of magnitude longer than the cooling time).

At the Galactic center, the situation is much more favorable. First, relativistic effects reduce the electrons oscillation frequency, so that they are resonant and can be directly accelerated without energy exchange with ions. Second, the amplitude of the instability is much stronger ($\sim$ 1.). And last, the dominant cooling process (synchrotron radiation) is comparatively much weaker. Namely, the radiative cooling time is comparable to the orbital time scale (Gillessen et al. 2006; Liu et al. 2006b):

$$\tau_{\rm sync} \approx 2 \text{ h} \left(\frac{\gamma}{10^2}\right)^{-1} \left(\frac{\rm B}{\rm 30G}\right)^{-2} \tag{2.2}$$

so that the acceleration efficiency is:

$$\frac{\tau_{\rm acc}}{\tau_{\rm sync}} \approx 0.2 \left(\frac{\gamma}{10^2}\right) \left(\frac{B}{30G}\right)^2 \left(\frac{R}{3R_s}\right)^{3/2} \left(\frac{b}{B_0}\right)^{-2} \left(\frac{\omega_c}{\Omega_K}\right)^{-1} \tag{2.3}$$

where B is the mean magnetic field, and $R/3R_s$ is the radius normalized to the radius of the last stable orbit. With these estimates, the acceleration is faster than the radiative cooling, showing that the magnetic pumping can be efficient. A more detailed treatment including precisely the relativistic effects is in preparation and will be published soon.

3 Conclusion

The Galactic center is known to host a supermassive black hole. This very peculiar environment is very interesting for high energy astrophysics. We have presented two issues related to plasma heating/particle acceleration. At large scales ($\sim$300pc), we have shown that a heavy plasma at a temperature of $\sim$ 7 keV can exist despite its high temperature and that it can be heated by viscosity. At smaller scale, we have presented a new acceleration mechanism. The magnetic pumping can balance the radiative cooling and heat the electrons to Lorentz factor of $10^2 - 10^3$ as required to interpret synchrotron self comtpon spectra.

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