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X-RAY EMISSION FROM COMETS, COMETARY KNOTS, AND SUPERNOVA REMNANTS

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ABSTRACT

A comparison is made between one of the processes leading to cometary X-ray emission and X-rays from supernova remnants. We demonstrate that the X-ray emission in both comet and supernova is bremsstrahlung and line radiation created by energetic electrons accelerated by plasma turbulence. We further demonstrate that the most likely source of plasma turbulence is produced by counterstreaming ion populations which result from the mass loading effect or from an anisotropic distribution produced by reflecting ions from a collisionless shock. The instability that gives rise to the plasma turbulence is the modified two-stream instability of counterstreaming ions. A similar instability arises in laser-plasma interactions that have self-generating magnetic fields and flowing ions.

Subject headings: comets: general — instabilities — radiation mechanisms: nonthermal — supernova remnants — turbulence — X-rays: general

1. INTRODUCTION

Counterstreaming plasma flows are produced in many astrophysical objects: in comets, a counterstreaming flow is set up between the solar wind and the cometary atmosphere; in supernova remnants, the reflected ions from the forward and reverse shocks form counterstreaming flows. Counterstreaming flows are well known in plasma physics to be responsible for a number of instabilities generating plasma waves. In a magnetized plasma, one of the most important is the modified two-stream instability (MTSI; McBride et al. 1972), which generates waves between the electron and ion gyrofrequencies known as lower hybrid waves. Lower hybrid waves are particularly important since they couple to both the electrons and ions and are capable of producing high-energy electrons. These waves have interesting properties: being able to resonate with ions moving across field lines and higher velocity electrons moving parallel to the magnetic field. This allows the wave to transfer energy from ion flows to electrons. For example, in the MTSI, ions moving across magnetic field lines drive up the waves, which then energize electrons moving along the magnetic field, producing high-energy electron tails. The MTSI is important at collisionless perpendicular shocks and can explain the energetic electrons observed, for example, at the earth's bow shock (Shapiro & Shevchenko 1988). In this paper, we show that the instability operates in comets and supernova remnants and is responsible for accelerating and heating electrons to keV temperatures.

Since the first successful detection of X-rays from comet Hyakutake in 1996 (Lisse et al. 1996), X-rays from more than 10 other comets have been observed. From the various observations, several conclusions can be drawn. (1) The energy of the X-rays is relatively soft in the hundreds of eV energy range. (2) The emission is confined to the cometary coma between the nucleus and the Sun, varying in extent from 10^4 to 10^6 km. (3) It appears not to be correlated with solar X-ray flux, and it appears not to be associated with dust or dust impacts. There is little doubt that the emission results from the solar wind/cometary atmosphere interaction. Supernova remnants also have a number of things in common with solar wind/comet interactions, namely the shock wave produced creates ring-type ion velocity distribution functions, which generate lower hybrid waves capable of accelerating electrons. Therefore, it is perfectly reasonable to propose that the X-ray emission mechanism from supernova remnants is similar, i.e., due to a high-energy electron tail produced by lower hybrid turbulence.

High-resolution *Hubble Space Telescope* (*HST*) images of the old planetary nebula NGC 7293 (the Helix Nebula) reveals many fine-scale filamentary structures. The filaments are generally referred to as cometary knots, and *HST* revealed that they have radii of 50–100 AU and lengths of order 1000 AU. They also have luminous cusps on the surface facing the hot central star which are photoionized and in hydrostatic equilibrium.

The similarity between the solar wind/comet interaction and the conditions surrounding cometary knots suggests that cometary knots are also sources of X-rays. This is an observation that has yet to be made.

In this paper, we describe a mechanism that could operate in all three situations, namely the production of X-rays by a combination of bremsstrahlung and line radiation from high-Z atoms. The electrons are energized by plasma turbulence generated by anisotropic ion velocity distributions, such as ion ring distributions due to pick-up processes in colliding plasmas or shock reflection of ions. In all three cases, we assume that we have a rapidly moving plasma colliding with a neutral or partially ionized gas.

Electron acceleration by lower hybrid waves generated by an ion streaming–type instability such as the MTSI is a phenomenon well known in magnetic fusion studies (Luckhardt et al. 1982) and to a lesser extent in laser fusion studies (Haines 1997), and it is also responsible for electron energization in many space environments (Bingham et al. 1994; McClements et al. 1993, 1997; Shapiro & Shevchenko 1988; Shapiro et al. 1999). In the cometary case, unstable ion distribution functions are produced by photoionization of the neutral gas outflow evaporated from the cometary nucleus (Bingham et al. 1997; Shapiro et al. 1999). In the supernova remnant case, unstable ion distributions are produced by either shock waves created by the shocked interstellar medium (ISM) or the shocked ejecta. Unstable ion distributions could also be due to the relatively fast component of the pulsar or neutron star wind mixing with the cooled neutral circumstellar wind, forming the pick-up scenario as in comets.

The emission of Lyα from SN 1987A has already been observed (Sonneborn et al. 1998) with the Space Telescope Imaging Spectrograph (STIS). The emission comes from a reverse shock formed where the outer envelope of SN 1987A strikes ionized gas inside the inner circumstellar ring. Michael et al. (1998) argue that it should be possible, using future STIS observations, to predict the time of the impact with the inner circumstellar ring. Soft X-ray emission from SN 1987A seen by *ROSAT* (Beuermann, Brandt, & Pietsch 1994; Hasinger 1996) can be explained by a model attributed to Chevalier & Dwarkadas (1995) in which the blast wave formed by the outer envelope of the supernova interacts with a relatively dense H II region (density $n_{\mathrm{H\,II}} \approx 10^2$ cm^{-3}). This H II region separates the shocked stellar wind of the supernova progenitor from the inner circumstellar ring. Chevalier & Dwarkadas (1995) estimate that the blast wave will strike the circumstellar ring around the middle of the next decade, producing a bright source of X-rays.

At the moment, the Lyα emission from SN 1987A is coming from hydrogen ions with radial velocity ~15,000 km s^{-1} interacting with the reverse shock. Such an interaction would result in plasma energization producing energetic electrons and ions, the electrons being responsible for bremsstrahlung and line radiation from high-Z atoms such as oxygen, carbon, and nitrogen.

Cometary knots imaged by the *HST* resemble in many ways the interaction of a real cometary atmosphere with the solar wind. Cometary knots are assumed to be the end result of the Rayleigh-Taylor instability in which a high-velocity wind interacts with a dense, slower moving component. This instability results in finger-like components with a head and tail feature similar in appearance to a real comet. At the present time, only optical images taken by *HST* exist. If these structures are the result of a high-velocity wind impacting a gaseous atmosphere, then X-ray emission should exist at the head of the cometary knots similar in appearance to the X-ray images of real comets (Lisse et al. 1996). In this article, we will outline the mechanism that can give rise to high-temperature plasmas and X-ray emission whenever we have interacting plasma volumes.

2. MODEL

The interaction of neutral gas with a collisionless plasma shock gives rise to a number of collective plasma processes. If the system has no magnetic field, which is considered unlikely, then ion-ion instabilities will thermalize the system.

If there are magnetic fields present, then the most likely collective process responsible for thermalization processes between counterstreaming ions is the MTSI. Due to charge stripping (electron ionization or photoionization) of the neutral atoms, a counterstreaming ion-ion instability results. The relative motion between the two populations provides the free energy to drive the instability.

In the presence of a magnetic field, the newly created photoions move in cycloidal orbits given by

$$v_x = u_\perp(1 - \cos \omega_{\mathrm{ci}} t) , \quad (1)$$

$$v_y = u_\perp \sin \omega_{\mathrm{ci}} t ; \quad (2)$$

here $u_\perp = cE_0/B_0$ is the transverse (to $\boldsymbol{B}_0$) velocity, $\omega_{\mathrm{ci}} = eB_0/m_i c$ is the gyrofrequency of the newly created ion, and $\boldsymbol{E}_0$ is the electric field seen by an ion at rest with respect to the flowing magnetized wind. In the wind frame, the newly created ions form an ion ring distribution. A similar type of ring distribution is formed by a wind interaction with a shocked medium. In this case, however, the wind ion is reflected moving upstream, and for a perpendicular shock it sees the convective electric field $\boldsymbol{v} \times \boldsymbol{B}$ resulting in a cycloidal orbit.

In the frame of the shock, the reflected ions form an ion ring distribution penetrating along the magnetic field $\boldsymbol{B}$ with velocity $u_\parallel$. These ions have a distribution function of the form

$$f_i(r, u_\perp, u_\parallel) = n_i \delta(v_\perp - u_\perp)\delta(v_\parallel + u)/2\pi u_\perp ,$$

where n_i is the density of the newly created ions and $u_\perp$ is their perpendicular velocity.

The interaction of this ion ring distribution with the ambient plasma behind the shock drives the MTSI, which results in strong plasma turbulence around the lower hybrid frequency range. The interaction of the ion ring or sometimes beam with the wind plasma drives the MTSI described by the following dispersion relation (Shapiro et al. 1999):

$$\frac{\omega_{\mathrm{LH}}^2}{\omega^2} + \frac{\omega_{\mathrm{ce}}^2}{\omega^2}\frac{k_\parallel^2}{k^2 + \omega_{\mathrm{pe}}^2/c^2} + 8\pi^2 i \int dv_\parallel \int_{\omega/k_\perp}^{\infty} dv_\perp \frac{\partial f_i/\partial v_\perp}{\sqrt{k_\perp^2 v_\perp^2 - \omega^2}} = 1 + \frac{\omega_{\mathrm{pe}}^2}{k^2c^2} , \quad (3)$$

where ω_{LH} is the lower hybrid frequency, and ω_{ce} and ω_{pe} are the electron cyclotron and plasma frequencies.

Lower hybrid waves have the following dispersion law:

$$\omega^2 = \omega_{\mathrm{LH}}^2\left(1 + \frac{\beta}{2k^2\rho^2}\right) + \frac{\omega_{\mathrm{ce}}^2(k_\parallel^2/k^2)}{(1 + \beta/2k^2\rho^2)^2} , \quad (4)$$

where ω_{LH} is the lower hybrid frequency

$$\omega_{\mathrm{LH}} = \sqrt{\frac{\omega_{\mathrm{ce}}\,\omega_{\mathrm{ci}}}{1 + \omega_{\mathrm{ce}}^2/\omega_{\mathrm{pe}}^2}} ;$$

$\omega_{\mathrm{ce},i}$ is the electron, ion gyrofrequency, ω_{pe} is the plasma frequency, $\beta = 8\pi n_0 T_i/B_0^2$ is the ratio of gas kinetic pressure to magnetic pressure, and $\rho = (T_i/m_e)^{1/2}(1/\omega_{\mathrm{ce}})$ is the electron gyroradius using the ion temperature T_i and density.

The integral over the transverse velocity $v_\perp$ of the gyrating ring ions on the left-hand side of equation (3) can be easily calculated using the ring distribution function or a beamlike distribution function with the growth rate being given by (Shapiro et al. 1999)

$$\gamma \simeq \frac{n_i}{2n_0}\frac{m_p}{m_i}\frac{\omega^2\omega_{\mathrm{LH}}^2}{k^3u_\perp^3}\frac{1}{1 + (\beta/2k^2\rho^2)} . \quad (5)$$

We have used here the notation m_i to depict the wind ion mass assumed to be hydrogen and m_p as the mass of the newly created ion or impact medium. For the cometary case, m_p is mostly oxygen (Lisse et al. 1996), since the cometary nucleus contains water and carbon dioxide; for the supernovae and cometary knots, m_p is the mass of the ejecta thought to be a mixture of different gases such as hydrogen, oxygen, carbon, and nitrogen and dust particulates for SN 1987A (Michael et al. 1998). In the case of an atomic mixture, m_p is determined by

$$\frac{1}{m_p} = \frac{1}{n_p} \sum_{\alpha} \frac{n_\alpha}{m_\alpha} ,$$

where α is the atomic species.

For the laser fusion scenario, we have a rapidly expanding plasma moving across a self-generated magnetic field. Such a model also produces waves at the lower hybrid frequency (Haines 1997).

These lower hybrid waves have a component of momentum $\hbar \boldsymbol{k}$ along the magnetic field, i.e., $\hbar k_{\|}$, $\boldsymbol{k}$ is the wavevector of the wave, which has a component principally perpendicular to the magnetic field. The wavevector $\boldsymbol{k}$ has two components: $k_\perp$ and $k_{\|}$. Using this fact and the fact that the waves are driven by the perpendicular velocity space component of the distribution function such that

$$v_{i\perp} \approx \frac{\omega}{k_\perp} ,$$

then it is possible for the wave to have a higher phase velocity component along the field direction, i.e., $v_{\mathrm{ph}\|} = \omega/k_{\|}$ and $v_{\mathrm{ph}\|} \gg v_{\mathrm{ph}\perp} \sim v_{i\perp}$. The component of the wave along the magnetic field has the possibility of resonating with faster, more mobile electrons and accelerating them through inverse Cerenkov resonance $\omega \approx k_{\|} v_{\mathrm{electron}}$. The waves grow as a result of the perpendicular (with respect to $\boldsymbol{B}$) motion of the newly ionized nitrogen ions and can interact simultaneously with the background ions and electrons.

The growth rate of the MTSI is typically $\simeq 0.1\omega_{\mathrm{LH}}$. A typical distance needed for the waves to grow exponentially, while they are convected through the plasma, is

$$r \simeq 10 u \gamma^{-1} \tag{6}$$

(the factor 10 is to allow for significant *e*-foldings).

In the shock frame, in steady state, the energy flux lost by the picked up ions is equal to the energy flux carried away by the energized particles, electrons, and ions associated with the envelope of the blast wave. The electrons gain energy parallel to the magnetic field, while the ions gain energy perpendicular to the magnetic field $\boldsymbol{B}$. Equipartition of energy takes place, with approximately $\frac{1}{3}$ going into electrons and $\frac{2}{3}$ into the ions (2 degrees of freedom for the ions perpendicular to $\boldsymbol{B}$, 1 degree of freedom for the electrons parallel to $\boldsymbol{B}$).

The following energy flux balance equation between electrons and ions can be written in the form

$$\alpha n_i m_i u^3 \simeq n_{Te} \epsilon_e \left(\frac{\epsilon_e}{m_e}\right)^{1/2} ; \tag{7}$$

α is a transfer coefficient of efficiency $\simeq 0.1$, n_i is the ion density for the supernova case, m_i is the ion mass, n_{Te} is the electron density, ϵ_e is the typical electron energy, and m_e is the electron mass.

By balancing the growth rate γ_{LH} of the lower hybrid waves due to the instability with the Landau damping rate due to the wave (inverse Cerenkov) interaction with energetic electrons, we obtain the following relation:

$$\frac{n_{Te}}{\epsilon_e} \simeq \frac{n_i}{m_i u^2} . \tag{8}$$

Combining this with equation (7) gives the following estimations for the typical energy ϵ_e of the suprathermal electrons and their number density:

$$\epsilon_e \simeq \alpha^{2/5} \left(\frac{m_e}{m_i}\right)^{1/5} m_i u^2 , \tag{9}$$

$$n_{Te} \simeq \alpha^{2/5} n_i \left(\frac{m_e}{m_i}\right)^{1/5} . \tag{10}$$

The distribution function of the electrons forms a high-energy tail along the magnetic field direction. Using equations (9) and (10), we can now estimate the luminosity for different astrophysical environments.

3. X-RAY PRODUCTION MECHANISMS

3.1. *Comets*

The cometary ion flux F_i at a distance r from the nucleus of the comet can be obtained by equating the photoionized part of the cometary gas outflow to the flow of the cometary ions picked up by the solar wind and is given by

$$F_i = 4\pi r^2 n_{\mathrm{ci}} u = Q_s - Q_s e^{-r/v_g \tau} = \frac{Q_s r}{v_g \tau} , \tag{11}$$

where Q_s is the initial flux of gas molecules at the comet surface ($= 2 \times 10^{29}$ molecules s^{-1}), τ^{-1} is the rate of photoionization ($\tau = 10^6$ s at 1 AU), v_g is the initial gas velocity ($v_g = 10^5$ cm s^{-1}), and n_{ci} is the cometary ion density. A more accurate calculation (Wallis & Ong 1975) based on the analysis of the solar wind dynamics, mass-loaded by the picked up cometary ions, leads to the same formula for the ion density. Using equation (11), we can estimate the density of the cometary ions n_{ci} to be ≈ 10 cm^{-3} for $u = 3 \times 10^6$ cm s^{-1}, which corresponds to the downstream shocked solar wind velocity at a distance $r = 50{,}000$ km, which is close to the position at which X-ray emission is being generated. These cometary photoions which are picked up by the solar wind excite the lower hybrid waves, which in turn are absorbed by the suprathermal electrons through Cerenkov resonance with the waves.

Using equation (9), we obtain the average energy of the suprathermal electrons to be ~ 100 eV and their density n_{Te} from equation (10) to be ~ 1 cm^{-3}. This is a powerful source of suprathermal electrons with an energy flux of 10^{19} ergs s^{-1} through the region of X-ray emission. The electron energy flux is about 2 orders of magnitude less than the total power available from the solar wind, indicating a reasonably high efficiency of energy transformation. This region also corresponds closely to the region in which intense lower hybrid waves were observed by the *Vega* satellite (Klimov et al. 1986) during its encounter with comet Halley. The presence of intense lower hybrid waves can result in field-aligned electrons accelerated up to energies in the keV range, exceeding significantly the average energy derived above (Bingham et al. 1997).

The maximum electron energy $\epsilon_{e_{\max}}$ can be obtained using equation (6) of Bingham et al. (1997),

$$\epsilon_{e_{\max}} \simeq \left[\frac{e^2}{2\pi m_e^{1/2}} \ell \langle E_f^2 \rangle\right]^{2/3} , \tag{12}$$

where ℓ is the interaction length, $\sim 10^9$ cm. Using for the wave energy spectral density values obtained from observations at Halley comet by the *Vega* spacecraft [$\langle E_f^2 \rangle \sim 1.0(mV^2/m^2$ Hz)], it is possible to estimate from equation (7) the maximum energy of accelerated electrons as

$$\epsilon_{e_{\max}} \sim 5 \text{ keV} . \tag{13}$$

We now make an estimate of the luminosity of the X-rays assuming that they are a combination of bremsstrahlung emission and inner shell radiation from collisionally excited oxygen atoms. For bremsstrahlung emission, the power radiated by one electron in 1 cm^{-3} is given by

$$g = \int \hbar\omega n_0 v_e \, d\sigma(\omega) , \tag{14}$$

where n_0 is the number density of water molecules ($= Q_s/2\pi r^2 v_g$) at distance r, v_e is the electron velocity, and $d\sigma(\omega)$ is the differential cross section for bremsstrahlung given by

$$d\sigma(\omega) = \frac{16}{3} \frac{Z^2 e^2 c}{\hbar v^2} r_0^2 \ln \left\{\frac{b_{\max}}{b_{\min}}\right\} \frac{d\omega}{\omega} , \tag{15}$$

where r_0 is the classical electron radius ($= e^2/m_e c^2$), Ze is the nuclear charge of the oxygen ion, ω is the radiation frequency, and $b_{\max}/b_{\min} = mv^2/\hbar\omega$. Note that $\ln\{mv^2/\hbar\omega\}$ is of order 1.

The power radiated in 1 cm^3 is $\int_{v_{\min}}^{v_{\max}} g f_e \, dv_e$, where f_e is the electron distribution function of suprathermal electrons. If the distribution function is constant in velocity up to a maximum value $v_{\max}$, then $f_e = n_e/v_{\max}$ and the total luminosity (in ergs s^{-1}) from a shell of thickness Δr surrounding the comet nucleus is given by

$$L = 2\pi \int g f_e \, dv_e r^2 \Delta r \simeq 3 \times 10^{-25} \times \frac{Q}{v_g} \Delta r n_e Z^2 \sqrt{\epsilon_{e_{\max}} \text{ (eV)}} . \tag{16}$$

In addition to bremsstrahlung radiation, there is also radiation from partially ionized oxygen and other heavy cometary ions whose bound electrons are excited by collisions with the suprathermal electrons. The bound electrons quickly de-excite and radiate any energy they receive from this source.

Line radiation produced by excitation of bound electrons in inelastic collision with keV plasma electrons is found to be more effective than bremsstrahlung. Detailed calculations of the intensity of this radiation known in fusion research as impurity radiation (Post et al. 1977) have shown that this radiation is a powerful source of energy loss in a fusion reactor. The basic physics of this radiation can be explained using the simple picture proposed in Dawson (1981), where it is assumed that the cross section of the process is determined by inelastic Coulomb electron-electron collisions with small impact parameter, thereby leading to relatively large angle scattering of plasma electrons. The total luminosity due to recombination or impurity radiation from the cometary shell, described earlier, is given by Post et al. (1977):

$$L_I \approx 5 \times 10^{-18} \Lambda n_e \frac{Q \Delta r}{v_g} \frac{1}{\sqrt{\epsilon_e \text{ (eV)}}} . \tag{17}$$

The numerical factor Λ for oxygen atoms has been estimated in Dawson (1981) as 0.1, which is close to the value obtained by detailed calculations (Post et al. 1977).

Using equations (16) and (17), we estimate the total luminosity of bremsstrahlung impurity radiation for the parameters we have used above as $L_I \approx 10^{15}$ ergs s^{-1} for photon energies in the keV energy range; this corresponds to an X-ray efficiency of 3×10^{-6}, which is comparable with the values obtained in terrestrial aurorae (Chamberlain 1961). X-ray luminosities for a number of comets have been calculated and compared to observations. The results are in very good agreement (Shapiro et al. 1999) and are within the error bars for each comet observation. We conclude that our model can describe the main mechanism for X-ray production at comets.

3.2. *Supernova Remnants*

The model of radiation emission derived in the previous section can easily be extended to the case of supernova remnants, for which plasma energization takes place by wave turbulence produced at shocks, where the ion distribution functions are similar to those found at comets, i.e., ringlike in velocity space.

The difference between the cometary case and the supernova remnant case is the velocity of the wind involved. For comets, the wind velocity is typically 400 km s^{-1}, and for remnants in particular the impact expected from SN 1987A has a wind speed of 15,000 km s^{-1}, considerably in excess of the solar wind.

The high impact velocity of the wind reduces the effectiveness of the coupling process. However, the shocked wind speed has a much lower velocity, creating the right conditions for lower hybrid generation in the downstream region.

The total luminosity (bremsstrahlung + line radiation) per unit volume is given by

$$L_{\text{tot}} = \left(3 \times 10^{-25} n_e n_0 Z^2 \sqrt{\epsilon_{e_{\max}} \text{ eV}} + 5 \times 10^{-18} \frac{\Lambda n_e n_0}{\sqrt{\epsilon_{e_{\max}} \text{ eV}}}\right) \text{ergs cm}^{-3} \text{ s}^{-1}$$

for $n_e \sim n_0 \sim 100$ cm^{-3}, $\epsilon_{e_{\max}} \simeq 10$ keV.

The luminosity per unit volume is 7×10^{-17} ergs cm^{-3} s^{-1}. This value is in reasonable agreement with observations.

3.3. *Cometary Knots: The Helix Nebula*

The Helix Nebula (NGC 7293) is a newly evolved planetary nebula. In the recent listing by Harris et al. (1998), it was listed as the second closest at a distance of 213 pc. When combined with its large size (12′ diameter), this makes the Helix one of the few planetary nebulae in which significant small-scale structure can be readily resolved. The Helix Nebula shows ionized knots that display comet-like tails, the so-called cometary knots (CKs). The CKs are radially oriented around the interior of the main nebula ring. The *HST* has now shown that these cometary knots are clearly resolved clouds, with neutral cores and photoionized surfaces facing the hot central star. The tails are formed from material streaming backward from these cores (O'Dell & Handron 1996; O'Dell & Burkert 1998). The central star itself has an estimated temperature of 123,000 K (Bohlin, Harrington, & Stecher 1982) and a luminosity of 120 $L_{\odot}$. Cerruti-Sola & Perinotto (1985) could find no evidence for a stellar wind. However, given the temperature of the star, many of the usual indicators of a wind might not be visible, even for a wind that is dynamically important. O'Dell & Handron (1996) examined 32 CKs that were well separated from other knots. Their sizes ranged from 125 to 390 AU (scaled by ~ 1.4 for the new distance). They also estimated individual masses of $(1–2) \times 10^{-5}$ $M_{\odot}$ and extrapolated to a total mass of the cometary knots of ~ 0.1 $M_{\odot}$ (or ~ 10 $M_{\rm Jupiter}$). From the surface brightness in Hα, O'Dell & Burkert (1998) estimate an electron density of 1200 cm^{-3} for the ionized portion of the knots and a density of $\sim 1 \times 10^6$ cm^{-3} for the neutral cores. The expected width of the ionization front is about $\sim 10^{15}$ cm.

O'Dell & Burkert (1998) were also able to confirm that the brightness distribution dropped exponentially with a density scale height of $(1–2) \times 10^{15}$ cm for Hα. This implies that the CKs are pressure bounded rather than freely expanding. The stellar wind from the hot star could provide the unobserved pressure without violating other observational constraints.

If we assume that the high-velocity wind speed from the central object is of the order of 1500 km s^{-1} with a relatively low density of 1 cm^{-3} with a comoving magnetic field of the order of several nanoteslas, which are consistent with those of the solar wind, then we can calculate the X-ray luminosity as in the previous sections. The main parameter we have to use is the density of the cometary knot at the interface with the wind, i.e., the region equivalent to the cometopause; we assume the maximum value to be 1200 cm^{-3}. The wind kinetic energy, assuming a proton plasma, is of the order of 12 keV. The wind will thermalize when it hits the CK, which will then raise the temperature at the front of the CK. This value could be of the order of several keV. Using these numbers gives a maximum flux of 10^{-14} ergs cm^{-2} s^{-1} for an oxygen plasma. This is larger than that emitted from either the comet or the supernova remnant and may just be observable. The difference in emission is due to the much higher density of the cometary knots.

4. CONCLUSIONS

In this paper, we have presented a model of X-ray emission from three astrophysical objects: comets, supernova remnants, and cometary knots. In all three cases, we assumed that the interaction between magnetized flowing plasma created a hot plasma medium in the keV range of temperatures, which was then responsible for bremsstrahlung and line radiation. A third candidate for X-ray emission is charge exchange. However, we have found previously (Shapiro et al. 1999) that although this process does occur in comets and could occur in these other objects, it was an order of magnitude less efficient in generating X-rays. A full calculation should take into account all three mechanisms. The energization of the plasma was by lower hybrid turbulence produced as a result of an instability well known in fusion plasmas, both magnetic and laser. This instability is found to occur in many laboratory and astrophysical plasmas. The model presented will need to be followed up by extensive numerical simulations, which we are doing at present.

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