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COOLING AND RECOMBINATION PROCESSES IN COMETARY PLASMA

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1. INTRODUCTION

It has long been recognized that collisional cooling and recombination processes are likely to be important in the inner cometary coma, in a 10^4km radius region for the larger comets (Biermann & Trefftz 1964) Cherednichenko (1970) laid stress on dissociative recombination processes, as possibly playing a role in the production of observed ions and radicals. Oppenheimer, in his spirited contribution to this conference, emphasized that a variety of ion-molecule interactions occur relatively rapidly and probably take part in the production of known cometary radicals.

In this paper, we focus our attention on the ion-electron plasma in comets and examine in the first place the cooling processes which result from its interactions with the neutral coma. For the plasma is generally very energetic (1-100eV) and must be cooled if it is to reach moderate densities and promote efficient particle-particle interactions. For example, solar wind electrons have 10-15eV energy, they experience some adiabatic heating (factor 2 or 3) in passing through the coma, they may gain around 10eV in passing through a collision-free, resistive shock and perhaps suffer additional heating via plasma turbulence effects. Photo-ionization processes may release other energetic electrons — He 584Å photons could give electrons with about 10eV (Biermann & Trefftz 1964), although most have less than 5eV.

New cometary ions produced at 10^5-10^6km in the far coma probably gain most of the streaming energy of the solar wind, through being accelerated in the $\underline{E}$ and $\underline{B}$ fields up to perhaps several thousand eV (Wallis 1973a). How quickly these ions are lost from the incoming solar wind plasma largely determines the ion pressure.

Cooling processes have general relevance for plasma behaviour in comets, in describing the overall plasma flow through the coma and in cometary plasma formation. Specific problems that have received attention and require a careful description of the cooling rate are that the visible ion structures cannot consist of hot and therefore low density plasma; that cool molecular-ion plasma is rapidly destroyed by dissociative recombination; and that energetic photo-electrons would exert a high pressure in the inner coma and prevent penetration by the solar wind. We develop a continuous description of the cooling effects in order to look at such problems.

In this preliminary examination, we shall consider a cometary coma composed predominantly of H_2O and its decomposition products (Wallis 1973b). For specific estimates, we use a comet of the size of comet Bennett 1970 II, with a production rate $Q = 10^{29}$ H_2O molecules $ster^{-1}s^{-1}$ at 0.7a.u. heliocentric distance. The coma density depends a little on assumptions about the expansion velocity V; this factor is relatively unimportant, but for concreteness and consistency, we suppose V increases with distance due to photo-dissociative heating (Wallis 1974), so that the density at radius R is

$$N = \frac{Q}{VR^2} \text{ where } \frac{Q}{V} \simeq \begin{cases} 4\times10^{23}\text{cm}^{-1} & \text{at } R>3\times10^4\text{km} \\ 10^{24}\text{cm}^{-1} & \text{at } R = 10^3\text{-}10^4\text{km.} \end{cases} \quad (1)$$

2. COOLING PROCESSES

Descriptions of electron cooling are given in planet ionosphere studies (Henry & McElroy 1968, Sawada et al. 1972, Olivero et al. 1972), energy loss rates in O, CO, H_2O etc. being computed on a continuous slowing-down approximation. Data for e-OH collisions are incomplete* and we suppose it comparable to CO above 7eV, while similar to H_2O with rotational transitions dominant at lower energies (Shimizu 1974). Ionization data for H_2O, OH and O have been summarized by Wallis (1973b).

Solar wind protons and energetic cometary ions are lost from the plasma primarily in charge exchange processes with neutral gas, having cross-sections $\sigma = 1\text{-}3\times10^{-15}\text{cm}^2$ at $10^3\text{-}10^4$eV.

Electrons are cooled in a variety of processes at rates varying with energy as shown in Fig.1. The functions shown are a continuous approximation to the discrete energy losses actually occurring which is useful in calculations (Olivero et al.1972). The approximation exaggerates the width of the 'holes' in the CO cooling

* But see I.V. Sushanin 1973 Problemi kosmich.fiziki 8, 88

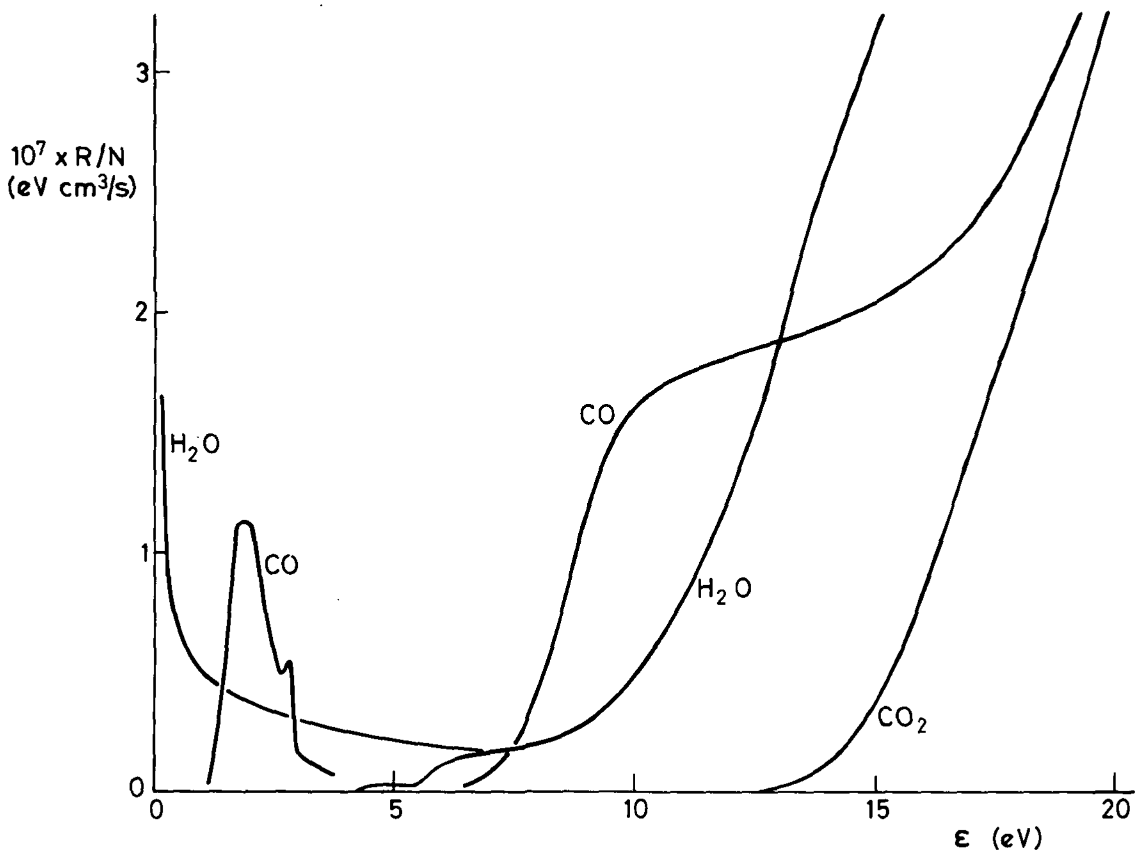

Fig. 1. Cooling rates for inelastic collisions of electrons with energy ε in molecular gases, on the continuous slowing-down approximation. The theoretical cooling rate via rotational excitations of OH is similar to that of H_2O (section to the left), but both are uncertain to a factor 3. The structured, low energy part of the CO curve is due to vibrational excitations.

function, where this becomes small or even zero. But after making allowance for the redistribution of energy between the electrons, which has to be done anyway, the inaccuracy due to the continuous approximation becomes small. For electron collisions with H_2O, rotational excitations dominate below 5eV and as each energy jump is small, the continuous approximation is good even for single electrons. The cooling rate, calculated on the rigid rotor approximation for electrons of energy ε exceeding $\Delta\varepsilon \simeq 0.025$eV has the form (personal communication from M.Shimizu)

$$d\varepsilon/dt \simeq N\sigma_{rot} v_e \Delta\varepsilon = -a\varepsilon^{-\frac{1}{2}}N, \quad a \simeq 5\times10^{-8}\,eV^{3/2}cm^3s^{-1}. \qquad (2)$$

Above 5eV, electronic excitations and ionizations become important (Fig.1) and the cooling rate increases steeply in 6-20eV as

$$d\varepsilon/dt \simeq -a'(\varepsilon-3eV)^2N, \quad a' = 2\times10^{-9}\ eV^{-1}cm^3s^{-1}. \qquad (3)$$

The time for cooling to the minimum energy $\Delta\varepsilon$ depends little on the initial energy if above 10eV:

$$t_{cool}^{-1} \simeq N\{\frac{1}{a}\int_{\Delta\varepsilon}^{6}\varepsilon^{\frac{1}{2}}d\varepsilon + \frac{1}{a'}\int_{6}^{\infty}\frac{d\varepsilon}{(\varepsilon-3)^2}\}^{-1} \simeq 3\times10^{-9}N\ cm^3s^{-1}. \qquad (4)$$

For electrons in CO, the cooling function is significantly structured (Fig.1), particularly because of the sharply-peaked vibrational excitations below 5eV. It is more meaningful to calculate the average cooling rate over a Boltzmann distribution, which turns out to be approximately linear above $\frac{1}{2}$eV:

$$d\bar{\varepsilon}/dt \simeq -b\bar{\varepsilon}N, \quad b = 1\text{-}1.5\times10^{-8}\mathrm{cm}^3\mathrm{s}^{-1}. \qquad (5)$$

Expression (5) is only applicable if thermalization processes are rapid enough. The thermalization rate due to Coulomb collisions is

$$t_c^{-1} = cn\varepsilon^{-3/2}, \quad c = 8\times10^{-5}\ \mathrm{eV}^{3/2}\mathrm{cm}^3\mathrm{s}^{-1}, \qquad (6)$$

which has to exceed the cooling rate of (5):

$$t_c^{-1} > bN \quad \text{or} \quad n/N > b\varepsilon^{3/2}/c. \qquad (7)$$

In practice, condition (7) is not fulfilled for 5eV electrons at densities found in the inner coma (Table 1). Plasma instabilities will therefore play a role in thermalization. For a highly anisotropic velocity distribution, the thermalization rate is a fraction of the plasma frequency (Davidson 1972)

$$t_\sim^{-1} \simeq 0.1\omega_{pe} \simeq dn^{\frac{1}{2}}, \quad d = 10\mathrm{cm}^{3/2}\mathrm{s}^{-1}. \qquad (8)$$

For the densities of Table 1, $t_\sim^{-1}$ exceeds bN by more than a factor 10. A more detailed treatment would modify (8) to include the damping effect of electron-molecule collisions, but this is estimated to be significant only inside 10^3km radius. The conclusion is that the anisotropy in electron energies will generate plasma turbulence, which produces some thermalization and limits the growth of anisotropy:

Table 1

Major ionization and recombination paths.

H_2O

$h\nu$

	OH^+	→	H_2O^+	→	H_3O^+	→	$H_3O^+ . H_2O$
reaction rate with H_2O		5×10^{-10} $cm^3 s^{-1}$		5×10^{-10} $cm^3 s^{-1}$		$10^{-27} N$ $cm^6 s^{-1}$	
e^-	$O+H$		$OH+H$		H_2O+H		$2H_2O+H$
α ($cm^3 eV^{\frac{1}{2}} s^{-1}$) for $\varepsilon<0.1eV$	$0.5-1\times10^{-7}\varepsilon^{-\frac{1}{2}}$		$5.5\times10^{-7}\varepsilon^{-\frac{1}{2}}$		$2.2\pm0.4\times10^{-7}\varepsilon^{-\frac{1}{2}}$		$4\times10^{-7}\varepsilon^{-\frac{1}{2}}$

The data is culled from Banks & Kockarts (1973), Cherednichenko (1970) and Leu et al. (1973). For electron energies exceeding 0.1eV, the dissociative recombination coefficients α may decrease as sharply as ε^{-2}. At the relevant cometary densities, the 3-body collisions producing $H_2O^+ . nH_2O$ are negligible.

expression (5) should remain an adequate approximation to the cooling rate.

The electron cooling functions (2) and (3) do not tend to give large anisotropies. Plasma instabilities are less likely to be important in thermalization and the unaveraged cooling rates should be appropriate.

3. IONOSPHERE OF THE H_2O COMET.

Suppose conditions in the inner coma are quasi-stationary with photo-ionizations being balanced by recombinations, changes due to the outward expansion being comparatively slow. Photo-ionization releases a spectrum of electrons, mainly below 5eV, which cool through vibrational excitations of the H_2O as (2) and subsequently recombine dissociatively. The ions may undergo ion-molecule interactions before recombining as shown in Table 1, but this makes little difference to estimates of plasma density.

The H_2O photo-ionization cross-section (Metzger & Cook 1964, Wantanabe & Jursa 1964) varies little over 12.6-18.3eV, so the electron energy spectrum in 0-5.7eV is close to the (shifted) solar spectrum:

$$P(\varepsilon) \simeq N\tau^{-1}\, j(1+\varepsilon/\varepsilon_*)^{-j-1}, \quad \varepsilon_* = 12.6\text{eV}. \qquad (9)$$

Here we have used a power law approximation to the solar spectrum (e.g. Shul'man 1972) with index $j \simeq 8.7$. With the continuous description of the cooling (2), the electron distribution function for energies above thermal where recombination is negligible is

$$f(\varepsilon) = \frac{\varepsilon^{\frac{1}{2}}}{aN} \int_{\varepsilon} P(\varepsilon')d\varepsilon' \approx \frac{1}{a\tau} \varepsilon^{\frac{1}{2}}(1 + \frac{\varepsilon}{\varepsilon_*})^{-j}. \qquad (10)$$

The solar 584Å photons contribute a further 10% by number to $P(\varepsilon)$ probably mainly in dissociative ionizations releasing electrons of 2-3eV energy, so are relatively unimportant. The 304Å and other far UV photons contribute fewer and more energetic electrons, which are very rapidly cooled according to (3) so are also unimportant. It is thus adequate to use expression (10) for the hot electrons, whose total number density and pressure do not exceed

$$\begin{aligned} \int_0^\infty f(\varepsilon)\, d\varepsilon &\leq \frac{\varepsilon_*^{3/2}}{j-1} \int_0^{\pi/2} \cos^{2k-4}\theta d\theta / a\tau \approx 40/cm^3 \\ \int_0^\infty \varepsilon f(\varepsilon)\, d\varepsilon &\leq \frac{\varepsilon_*}{2j-3} \int_0^\infty f(\varepsilon)\, d\varepsilon \approx 35\ eV/cm^3. \end{aligned} \qquad (11)$$

The numerical estimates apply for the ionization time $\tau = 10^6$s (at 0.7a.u). They are uncertain by a factor 2 or more because of uncertainty in the constant a, taken from (2).

Let us suppose for simplicity that recombination processes occur relatively slowly, so that recombination occurs only subsequent to cooling to thermal energies. This is valid if the density of thermal electrons is far greater than the density of energetic ones by (11).

Neglecting transport effects, the steady state balance of ionization and recombination rates is then

$$N/\tau = \alpha n^2$$

where α is the relevant dissociative recombination coefficient of Table 1. Thus the density of thermal electrons is

$$n = (N/\alpha\tau)^{\frac{1}{2}} \simeq 0.5\text{-}1.5\ N^{\frac{1}{2}}\ cm^{3/2}. \qquad (12)$$

Specific values of n(for $\alpha = 2.5 \times 10^{-7} \Delta\varepsilon^{-\frac{1}{2}} cm^3 eV^{\frac{1}{2}} s^{-1}$) are given in Table 2, and clearly exceed the density (11) of the energetic electrons inside 10^5km radius. The lifetime of an ion before recombination is $(\alpha n)^{-1} = \tau(n/N)$, which is far shorter than an e-folding time for changes due to the flow, $R/2.3V$, so ion transport effects are indeed negligible. It can also be confirmed that electron thermal conductivity is adequately limited by e-H_2O collisions.

In the inner coma, this ionospheric plasma is closely coupled to the neutral gas and streams radially outwards with it. Outside some radius of the order of

$$Q\sigma/V \simeq 3 \times 10^4 km, \qquad (13)$$

ion-molecule collisions become infrequent and the plasma can behave as a separate fluid with a smaller mean free path fixed by gyro-radius or collective plasma effects. A tangential discontinuity might exist between the ionospheric plasma and the plasma of solar wind origin (Wallis 1973b, Schmidt 1974). The ionospheric ions and electrons would exert a pressure of the order of their stagnation pressure

$$P(\text{stag}) = \int \varepsilon\, f(\varepsilon)\, d\varepsilon + n(\Delta\varepsilon + kT_i + m_i V^2). \qquad (14)$$

The first term representing the suprathermal electrons is given by (11) and, on equating T_i to the neutral gas temperature T, the values of P(stag) given in Table 2 are found.

This quantity P(stag) is to be compared with the solar wind stagnation pressure, which is of order 10^4eV cm^{-3} at 0.7a.u. This would place the ionosphere discontinuity and stagnation flow region within 10^3km sunward of the comet, impossibly far inside the decoupling radius (13). If the dissociative heating and and enhanced expansion velocity of the present model coma are discounted, the values of P(stag) would be lower and the concept of a plasma contact discontinuity still more dubious.

4. PLASMA FLOW THROUGH THE COMET COMA.

As long as the ionospheric plasma pressure is low (section 3), the solar wind plasma can flow on into the inner coma. We consider that it picks up new cometary ions and loses those neutralized in charge exchange processes in interactions with the neutral coma (Wallis 1973a). There is no sudden change at the scale coupling radius $Q\sigma/V$ (13), and we can expect the flow to penetrate far inside this position. We are interested

Table 2

Parameters in an H_2O coma.

R (km)	V (km/s)	T (°K)	kT+mV^2 (eV)	N (cm^{-3})	n (cm^{-3})	P_{stag} (eV/cm^3)
10^2	0.55	350	0.08	2×10^{10}	1.1×10^5	1.2×10^4
10^3	0.8	750	0.18	1.3×10^8	8.6×10^3	1.8×10^3
10^4	1.5	2800	0.67	7×10^5	6.3×10^2	4.7×10^2
10^5	2.6	(650)	1.27	4×10^3	50	100

Source strength $Q = 10^{29}$ molecules ster^{-1}s^{-1}. The neutral gas expansion velocity V, density N and temperature T are taken from the heated coma model of Wallis (1974), but T at 10^5km is uncertain. The plasma density n and stagnation pressure are calculated for solar radiation conditions at 0.7 a.u. heliocentric distance.

here in how rapidly the plasma can cool and condense.

There is no flow solution yet available for this strongly interacting and strongly cooled plasma flow, so we shall in making definite estimates assume that the plasma velocity in the incoming flow sunwards of the comet is

$$u = R/\tau_f, \qquad \tau_f \simeq 10^3 s, \tag{15}$$

τ_f being an empirical flow time scale which fits in with the outer flow solutions in the 1-5x10^{5}km region (Wallis 1973a,b). The assumption (15) is not critically important: if in error, the distance scale that we derive is simply distorted.

The cometary ions are rather energetic: they take up most of the streaming energy of the decelerating flow and have gyration velocities of the order of the flow velocity $v_* = R_*/\tau$ at the place where they become ions. They are lost primarily through charge exchange, so their distribution function $g(v_*)$ satisfies

$$\frac{dg}{dt} = -u \frac{dg}{dR} \simeq - \frac{Q\sigma}{VR^2} v_* \, g. \tag{16}$$

This equation neglects increases in ion energies due to continuing adiabatic compression. The solution to (16) using (15) and taking V as constant is

$$g(v_*) \sim \exp \ell_i^{\,2}(R_*^{-2} - R^{-2}), \tag{17}$$

where

$$\ell_i = \ell_i(v_*) = \{\tfrac{1}{2} \tau_f \, \sigma(v_*) \, v_* \, Q/V\}^{1/2} .$$

The number is reduced by a factor e by the position $R = \ell_i$ and a further factor e by $R = 0.7\ \ell_i$. Numerically ℓ_i is $3\text{x}10^4$km for initial ions of 600km/s velocity and $\ell_i = 2\text{x}10^4$km for the 50km/s ions formed at $5\text{x}10^4$km. The solar wind protons have thermal speeds of the order of 50-100km/s, so the corresponding disappearance scale is $\ell_p = 2\text{-}2.5\text{x}10^4$km.

The electrons in the inflowing plasma also cool rapidly due to various ionization and excitation processes. We suppose the cooling rates of (2) and (5) are representative in the mainly O and OH coma in 10^4-10^5km. The electron energy is perhaps ε_0=50eV at $R_0 = 10^5$km and decreases as

$$\bar{\varepsilon}/\varepsilon_0 \simeq \exp - \ell_e^{\,2}(R^{-2} - R_0^{\,-2}), \quad \bar{\varepsilon} > 6\text{eV}, \qquad (18)$$

according to (5) with (15), the scale radius being

$$\ell_e = \{\tfrac{1}{2}\ b\tau_f\ Q/V\}^{1/2} \simeq 2\text{x}10^4\text{km}. \qquad (19)$$

The mean energy reaches 6eV at $R_1 \simeq 1.5\text{x}10^4$km and would be 1eV at 10^4km by formula (18), but even faster cooling according to expression (2) is appropriate:

$$(6\text{eV})^{3/2} - \bar{\varepsilon}^{3/2} \simeq \frac{3}{4}\ \frac{Q}{V}\ a\tau_f\ (R^{-2} - R_1^{\,-2}). \qquad (20)$$

The electrons become fully cooled, it follows, at the position

$$\{R_1^{\,-2} + (6\text{eV})^{3/2} 4V/3Qa\tau_f\}^{-\frac{1}{2}} \simeq 1.0\text{x}10^4\text{km}. \qquad (21)$$

So in the absence of heating mechanisms, such as plasma turbulence transferring energy from the ions, the electrons cool explosively fast between positions ℓ_e — $\frac{1}{2}\ell_e$.

If plasma is to flow from the coma out laterally into tail rays, it is clear that the same scale radii are important. For example, suppose that flow occurs at constant radius and speed (the pressure gradient balancing the effective friction).
We replace d/dt in (16) by $R\tau^{-1}$ d/ds and obtain

$$g \sim \exp - \tfrac{1}{2}\ell_i{}^2(s-s_0)/R^3.$$

With flow distance $s-s_0 = \pi R/2$, we see that most of the ions would be lost if $R \lesssim \ell_i$. Similarly, the electrons would be strongly cooled if the lateral flow takes place at $R \lesssim \ell_e$. Coincidentally, these ion and electron scales are very similar in magnitude.

5. DISCUSSION

Solar plasma plus accumulated cometary ions and electrons is affected very strongly as it flows into the coma from $2\mathrm{x}10^4$ to 10^4km (this value for the comet with $Q = 10^{29}$ H_2O molecules $\mathrm{ster}^{-1}\mathrm{s}^{-1}$. The scale distance $\sim Q^{1/2}$.) The electrons are rapidly cooled and all but some 10% of the ions undergo charge exchange. This behaviour is not sensitive to our assumption (15) for the flow velocity, since it occurs explosively quickly. We conclude that this $1\text{-}2\mathrm{x}10^4$km region is effectively a transition region over which the outer plasma carrying the energy and ion flux of the solar wind changes continuously to plasma created and energised by the solar radiation. The purely cometary ionospheric plasma, flowing outwards with the expanding gas coma, would have stagnation pressure only 10% or less of that of the solar wind at the transition position — it can hardly affect the flow there. Although a stagnation region must occur in the plasma flow at some smaller radius, there will be no "tangential discontinuity" between plasmas of different nature or velocity.

An important characteristic of the ionospheric plasma is that the photo-electrons can cool rapidly to thermal energies before recombining. Rotational excitations of H_2O or OH are effective in the case considered. However, if the coma consisted for example of pure CO, the cooling mechanism would be more complex (section 2), with plasma turbulence trying to thermalize an anisotropic distribution of electron energies. The corresponding plasma pressure and density might be higher and significantly affect the transition flow. But in the H_2O comet, the conclusion is clear, that the pressure of the ionospheric plasma is unimportant.

We have assumed a model coma heated by photo-dissociations of H_2O, this model having a higher expansion velocity and temperature and larger ionospheric stagnation pressure. If there is no such heating, the plasma pressure would be lower. Shimizu (1974) has questioned the reality of the heating in the H_2O coma, on the grounds that rotational excitations rapidly remove the energy of the H-atoms. Indeed, the energy transfer from 1-2eV H-atoms to the rotational mode appears to be comparable to the elastic transfer to translational energy (σ_{rot} is higher by a factor 10, but the energy transferred is about 0.025eV rather than 0.2-0.4eV). This indicates that part of the photo-dissociation energy is available for heating and increasing the expansion velocity of the coma. The conclusion that the coma temperature is very low (Shimizu 1974) depends on the achievement of thermodynamic equilibrium between the rotational levels of H_2O, and is inapplicable at the relevant coma densities (Table 2) of $10^8 cm^{-3}$, or less.

The plasma interaction with the coma gas imposes strong limits on the place of origin of cometary ions which are to form tail rays. For plasma moving at around 10km/s velocity within the ℓ_i, $\ell_e \simeq 2x10^4$km scale is frictionally decelerated, strongly cooled and liable to recombination long before it can flow away. It appears impossible for plasma to emerge from inside 10^4km radius to form tail rays and streamers. In the transition region at 1.5-2.5km radius, the plasma can be cooled to give increased density and still flow away before recombination occurs. As such plasma expands adiabatically into tail rays, the recombination rate per unit mass changes as

$$\rho\alpha \sim \rho T^{-k} \sim \rho^{-k(\gamma-1)+1}, \tag{22}$$

decreasing with ρ for $k \simeq \frac{1}{2}$ (Table 1). Recombination decreases in importance, despite the adiabatic cooling.

This confirms assumptions of the earlier analysis of a tail ray (Wallis 1967) as a jet of plasma, initially cold but not undergoing recombination, ejected into the solar wind plasma where it is conductively heated and frictionally accelerated. The particular transport coefficients assumed were based on the transverse instabilities of velocity anisotropics in an unmagnetised plasma, on which much work has been done recently (Davidson 1972). As the magnetic fluctuations were found to exceed the expected intensity of any large-scale field, the unmagnetised ion-ion instability is indeed appropriate, but the postulated electron-ion instability may be eliminated by electron gyro-radius effects. The order-of-magnitude linear growth rate is, however, unchanged. Moreover, the demonstration that the non-linear process limiting the instability growth is ion trapping (Davidson 1972), confirms the earlier assumption (Wallis 1967) equating the growth rate to an effective collision or "bounce" frequency. So we consider that the earlier results need little modification. They imply, we recall, that there was substantial extra mass over and above the observed CO^+ in the tail rays examined - this might well be C^+, O^+ or OH^+.

Values of the CO^+ density in the coma at 10^4km radius have been given by Arpigny (1965) as $400cm^{-3}$ in comet Bester (at 1.0a.u.) and $600-1000cm^{-3}$ in comet Humason (2.6a.u). These are the same order as the ionospheric density (Table 2), although with the lower ionization rate at 2.6a.u., the CO production rate would have to be higher than $10^{29}ster^{-1}s^{-1}$. Alternatively the transport effects of ions being swept in by the solar wind flow can enable higher densities to be reached. It is noteworthy that 'envelope' and jet structures were observed in comet Bennett at $1-3x10^4$km ahead of the nucleus (Wallis 1973b). The appearance of structures at this position corresponds well with the present argument that cooling is important in allowing condensation of the plasma swept in with the solar wind. However, the mechanism for producing structures rather than continuous flow is not yet explained.

When ion-electron recombination is the dominant loss process, a recombination instability exists (D'Angelo 1967) if the coefficient $\alpha \sim T^{-k}$ varies rapidly,

$$- k (\gamma_e-1) + 2 < - 1 . \qquad (23)$$

If electron energies were as high as thermal energies 0.25eV at 10^4km (Table 2), the index may be as high as k = 2 (Leu et al. 1973), and the plasma might thus be unstable to compressional waves along the magnetic field (γ_e = 3). However, the energy transfer due to rotational excitations would exceed that due to recombinations by a factor

$$6 \times 10^{-8} \varepsilon^{-\frac{1}{2}} N / 3 \times 10^{-7} \varepsilon^{\frac{1}{2}} n,$$

approximately 500 at 10^4km (Table 2). The recombination instability might still operate far out in the coma and perhaps lead to the formation of 'knots' and other irregularities in tail rays. But some other process must underlie the formation of envelopes, probably a combination of dynamical with ionization and cooling effects.

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DISCUSSION

H. Keller: The outflow velocity used by Wallis is $\sim 3\text{-}4\,\mathrm{km}^{-1}$ (for H_2O, OH..) on the argument of heating by dissociative excess energies whereas some observations show only $\sim 1\,\mathrm{km\ s}^{-1}$ (that means no heating of the neutral component). Observations are necessary.

H. U. Schmidt: There may be a misunderstanding. In my discussion I assumed a negligible contribution to the temperature from the electrons, so that the pressure on the contact surface comes from the expansion of the remaining ions with 1 or 3 km/sec. I think your calculations are extremely valuable for another purpose, too, i.e., the electrical conductivity which can be obtained is important in the same context.

M. K. Wallis: Well, I agree that I've ignored things like electron conductivity. One can take the view that conductivity is high along the field lines. I would rather take the view that the plasma is rather turbulent and the conductivity on the field lines is not going to be that much different from conductivity across the field lines. I agree this is speculation and that it is something that needs to be looked into at some stage.

When you use conservation procedures like this, then you've got to be on your guard against that. But the ion pressure, I thought I understood you to say earlier that the momentum contribution of the outflowing ions, was unimportant. It was more the magnetic stresses which were bigger in effecting the pressure.

I don't have an outside and inside. There were two models. One is flowing in, straight in to the comet and the other one is looking at the plasma density in the inner region when you don't have any addition of plasma flow in It's just from the photoelectron plasma.

Now, these two regions have to be matched, of course, and you will have some ion pressure. But I'm cooling my electrons down so fast that I'm going to recombine the ions.

Now, it may be if you add that in it doesn't — that you get a bigger contribution. I'm not clear on that. We'll have to see.