Contemporary Physics, 1991, Vol. 32, no. 2, 73–88

A plain man's guide to the cometary environment

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Comets, volatile bodies whose environment depends on their distance from the sun, are presented in a way which highlights the essential physical processes involved. The contributions of past space missions such as Giotto and VEGA are discussed, as well as the potential benefits which might accrue from future missions such as CRAF.

1. Introduction

What is a comet?

Etymologically comets, 'hairy things', owe their name to their visual appearance as compact objects – 'heads' – trailing a long and diffuse structure. This structure is not permanent; it grows as the comet approaches the sun and dies away as the comet recedes, and we shall see that its very existence already furnishes a clue as to the typical size that the 'head' must have.

To each specialist his comet. To the planetologist searching for clues about the origin of the solar system, a comet is a potential source of information about primordial conditions in the 'solar nebula', and how this material evolved into the system we see today; to the gas phase chemist, the cometary atmosphere is a marvellous 'kitchen' in which to study the way exotic chemical

solid state experts extract much fun from building models of the solid material; in the cometary environment, the plasma physicist finds a strange medium in which ionized material is mixed with dust, the whole interacting with the interplanetary medium and its magnetic field in ways virtually impossible to simulate in the laboratory; finally, comets can be used as 'tracers' to study other problems, such as the general conditions of the interplanetary medium, or the mechanics of the complex gravitational field of the solar system.

Naïvely, one might think of a comet as a kind of very tiny planet; however, whereas a given planet is always embedded in much the same interplanetary medium and has a virtually unchanging radiation budget, comets, whose orbits are highly elliptical, are subject to continuously changing external conditions. This fundamental difference allows one to think of comets as compact and generally invisible sources of diffuse material, whose behaviour and appearance are driven by particular boundary conditions: this is the *leitmotiv* of this paper.

In short, we shall not explain *what* a comet is, rather investigate the physics which makes it look the way it looks. And figure 1 is a remarkably clear, albeit old, drawing of how a comet looks – it shows Donati's comet on the 5th of October, 1858, over Paris. The view is roughly west in the early evening (as one can see from the traffic on the bridge). Donati's comet was an admittedly spectacular object, rated as one of the best of the century; in particular, one can distinguish essentially two classes of tail, one class straight (itself doubled), pointing towards where the Sun set, the other curving away – even in this sketch, one has the feeling that the two tails must be of a totally different nature. A reasonably knowledgeable amateur astronomer will immediately recognize some of the constellations and deduce the angular scale of the drawing, from which he will find that the tails extend over roughly 30°; since at that date, the comet was about ninety million kilometres from the Earth, the tails turn out to be about fifty million kilometres long, a quite respectable distance. And the separation between the two straight tails is about one tenth of the length.

Finally, this drawing suggests that the cometary environment is surely very tenuous: the stars can be seen *through* the tails.

Modern spectroscopic observation adds one other fundamental piece of information: the spectrum of the curved fan-shaped type of tail is dominated by a continuum similar to that of the Sun, suggesting the reflection and diffraction of light, while the straight tails are sources of emission lines, indicating the presence of an excited gas.

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0010-7514/91 $3.00

Figure 1. Donati's comet, shown over Paris on October 5, 1858. (A. Guillemin, *Le Ciel*, 1877; Observatoire de Paris, photo Counil).

2. Growing a head of hair

Comets are on highly elliptical orbits; a fundamental observation (see for example Delsemme (1984)) is that the intrinsic brightness of a comet (that is, its brightness taking account of its distance from us) increases as it approaches the Sun from the farther reaches of the solar system much faster than the inverse square of its heliocentric distance. From this, we deduce that changes in the structure of the cometary surface are induced by solar heating; the changes are interpreted as due to the ejection of material creating an increasingly bright extended structure.

The variation of the brightness as a function of heliocentric distance seems to fall in two reasonably distinct régimes: far from the Sun, the brightness increases rather rapidly as the distance decreases, until (in most cases) the comet is roughly 3×10^8 km from the Sun (the Earth's orbital radius is about 1.5×10^8 km); closer to the Sun, the brightness variation as a function of distance begins to flatten out, after which the familiar cometary tail begins to grow. This critical region appears to govern other cometary phenomena; molecular emission spectra make their appearance a little earlier.

This behaviour can be easily interpreted in terms of the evaporation of volatile material from the central body.

Consider a very elementary model, which ignores all structural details: a sphere of volatile material, radius R, assumed to be perfectly absorbing and to emit like a perfect black body at temperature T, is at a heliocentric distance d. Suppose for simplicity that the sphere is rotating so rapidly that we may consider all parts of its surface to be equivalent; we then have:

$$\text{power radiated at the solar surface} = F_\odot = 3{\cdot}9 \times 10^{26}\ \text{W}, \tag{1}$$

$$\text{power absorbed by the comet} = F_\odot \frac{\pi R^2}{4\pi d^2}, \tag{2}$$

$$\text{power radiated by the comet} = 4\pi R^2 \sigma T^4, \tag{3}$$

where σ is Stefan's constant. Now, at its ambient temperature, the volatile material evaporates producing a flux (number of particles per unit surface) Z; if the latent heat of evaporation per particle is L:

$$\text{power used for evaporation} = 4\pi R^2 LZ. \tag{4}$$

Let us now suppose that thermal equilibrium has been attained; we then have:

$$F_\odot \frac{\pi R^2}{4\pi d^2} = 4\pi R^2 \sigma T^4 + 4\pi R^2 LZ, \tag{5}$$

whence:

$$\frac{F_\odot}{4\pi d^2} = 4\sigma T^4 + 4LZ. \tag{6}$$

Now, if the vapour is in equilibrium with the underlying solid surface, the flux of evaporating particles Z is directly proportional to the saturation vapour pressure P, the relation between them being given by (for example, see Tabor 1985)

$$Z = n\langle v\rangle/4, \tag{7}$$

$$P = nkT. \tag{8}$$

where n is the number density of evaporated particles, and their mean velocity $\langle v\rangle$ is given by:

$$\langle v\rangle = \sqrt{\left(\frac{8kT}{\pi\mu m_p}\right)}. \tag{9}$$

Here, μ is the mass of the particles in units of the proton mass m_p (in all estimates, we shall take $\mu = 18$, the value for water, for reasons which will emerge shortly), and k is Boltzmann's constant; we have assumed a Maxwellian velocity distribution. Finally, therefore:

$$Z = \frac{P}{(2\pi\mu m_p kT)^{1/2}}. \tag{10}$$

Making these substitutions and rearranging, equation (6) becomes:

$$\frac{1}{d^2} = \frac{16\pi\sigma T^4}{F_\odot} + \frac{16\pi LP}{F_\odot(2\pi\mu m_p kT)^{1/2}}$$

$$= 7 \times 10^{-33} T^4 + \frac{0{\cdot}3LP}{(\mu T)^{1/2}}. \tag{11}$$

The saturation vapour pressure P increases with temperature in a roughly exponential way – this is easily understood in physical terms (see Tabor (1985)), actual graphs for a number of volatile solids being given in Delsemme and Swings (1952). The latent heat L, however, is rather less sensitive to temperature.

The nearly exponential variation of P with temperature has an important consequence:

- for sufficiently low temperatures, the second term on the right-hand side of equation (11) is negligible with respect to the first term; low temperatures being related to large values of d, we conclude that far from the Sun the cometary temperature varies inversely with the square root of the heliocentric distance;

- there is some temperature beyond which the second term must dominate; closer to the sun than the corresponding distance, the temperature will rise much more slowly than the inverse root of the distance; physically, this comes about because an increasing fraction of the incident solar energy is being used to vaporize the material rather than to heat the surface.

Clearly, equality of the two terms on the right-hand side of equation (11) defines a region where the comet has become in some sense quite active. Using figure 1 of Delsemme and Swings (1952) which shows how the saturation vapour pressure of different volatiles varies with temperature, one finds easily that the two terms are comparable at a temperature, in round figures, of 200 K in the case of water ice ($L = 8 \times 10^{-20}$ J per molecule = 0·5 ev per molecule), and 100 K in the case of CO_2 ice (whose latent heat of sublimation is about one half that of water ice). From equation (11), we see that a temperature of 200 K is attained at a distance of a little over 2×10^8 km, and 100 K at just under 10^9 km.

In practice, cometary activity will already be reasonably vigorous at distances a little larger than the two limits (for water and CO_2 ice respectively) estimated above, since the two terms of equation (11) are not equally sensitive to temperature; in the case of water ice, one might expect the appearance and characteristics of a comet to change significantly already at about 3×10^8 km.

In conclusion, *if* a block of pure water ice were on a trajectory approaching the Sun, it would start to evaporate strongly at a heliocentric distance of about 3×10^8 km, as is in fact observed; other pure volatile solids become 'active' much farther out. This is the essential reasoning which leads one to believe that the volatile component of most comets is essentially water ice – the so called 'dirty snow ball' model (Whipple (1950)). In all the calculations which follow, we shall thus put $\mu = 18$.

The semi-quantitative approach we have taken above *is* to some extent internally inconsistent – tabulated values of saturation vapour pressure correspond to a closed situation, whereas we are interested in an open one. Nevertheless, since the cometary temperature is not a very sensitive function of heliocentric distance, this inconsistency cannot affect in a significant way estimates related to the temperature, while the simplification it allows has the merit of giving one an idea of the production rate of water molecules when the comet has become truly active; in this case the second term in equation (6) dominates, giving:

$$Z \approx \frac{F_\odot}{16\pi L d^2}. \tag{12}$$

Putting $L = 8 \times 10^{-20}$ J per molecule, the production rate at, say, the orbital distance of the Earth (this is an arbitrary but convenient choice, and the subsequent calculations will be done for this distance) comes to about 4×10^{21} molecules $m^{-2}\,s^{-1}$.

Were the 'head' in fact a block of pure water ice, its surface would thus at the orbital distance of the Earth have stabilized at a temperature of close to 200 K and, using equation (9) for the mean thermal velocity, would be expelling material at a velocity of $\langle v \rangle \approx 500\ m\,s^{-1}$.

These considerations already enable us to make an educated guess of how big a cometary nucleus might be. At the orbital distance of the Earth, a comet has generally developed a visible atmosphere whose size exceeds, say, 100 000 km, and a much longer tail which is clearly a weakly bound structure continuously losing matter which is replaced by material ejected from the nucleus. Thus, very roughly, the thermal energy of the escaping material, kT, is at least equal to its gravitational binding energy $GM\mu m_p/R$, where M is the mass of the nucleus, R its radius, and G the gravitational constant. Thus:

$$\frac{GM\mu m_p}{R} < kT, \tag{13}$$

whence, substituting the density ρ:

$$R < (3kT/4\pi\rho G\mu m_p)^{1/2} \tag{14}$$

Substituting our nominal cometary temperature of 200 K, still assuming that water is the dominant component and that the mean density of the nucleus is $1000\,\mathrm{kg\,m^{-3}}$, we obtain:

$$R < 600\,\mathrm{km}. \qquad (15)$$

Now, it is easy to show (see Weisskopf (1975)) that an icy object whose characteristic dimension is less than a few hundred km need not necessarily be spherical–self gravitational forces are insufficient to bring it into 'hydrostatic' equilibrium (it is not much more difficult to show that the same limit is true for any kind of normal natural material (Celnikier 1989).

Straightforward observation of the cometary hair thus leads to a sort of 'identikit' picture of its head–a volatile central object, smaller than a few hundred km, quite possibly having an irregular form, surrounded by an extensive atmosphere.

How does this picture correspond to what is known?

The radii of *bona fide* cometary nuclei are very badly determined since, with the single exception of the Halley encounter (see *Nature* (1986)), none has been seen directly. When comets are sufficiently close to the Earth to be resolvable, they are surrounded by an opaque atmosphere; at distances where the atmosphere is negligible, they are not resolvable, and the radii are more often than not inferred from their observed brilliance, *assuming* a plausible, but quite arbitrary, coefficient of reflectivity (other techniques include the analysis of their infra-red emission, and the use of radar). The largest nucleus inferred from modern observations had a characteristic dimension of about 80 km; studies of the variations in the luminosity of a few selected comets suggests an irregular form (A'Hearn 1988).

Cometary densities are remarkably badly determined (Peale 1989); apparently, in spite of considerable effort, the best buy is $1000\,\mathrm{kg\,m^{-3}}$, perfectly compatible with that of the 'identikit' comet (but for quite different reasons).

The nucleus of Halley's comet was seen via the Giotto and VEGA imaging experiments to have a very irregular shape – along a short axis, its size was 8 km, while along a long axis, it turned out to be 15 km. Representing such an object by a sphere of radius of 5 km, equation (12) integrated over the entire surface (giving a quantity which we shall refer to below as Q) suggests that the comet should be emitting at the heliocentric distance of the Earth:

$$Q = 4\pi R^2 Z, \qquad (16)$$

$$= 10^{30}\ \text{molecules}\ \mathrm{s^{-1}}. \qquad (17)$$

The Giotto measurements, carried out at 0·9 of this distance, lead to an emission rate of $0{\cdot}7 \times 10^{30}$ (Krankowsky *et al.* 1986).

In fact, we know that comets are not that simple; volatile material is only one component, and its ejection from the surface must liberate a more refractory 'dusty' material, of which certain aspects will be discussed in section 7. The Giotto images (of which figure 2 is a good example) showed that emission need not be isotropic; Halley's comet was clearly observed to have a number of 'jets', a phenomenon which had already been suspected from earlier ground based photographs. Indeed, it is now believed that only a small fraction of the surface of Halley's comet feeds its atmosphere, which suggests that the good agreement of our numerical estimates might be a little fortuitous. On the other hand, the images did show a very dark surface, just the kind of albedo we have assumed so far.

Cometary surfaces are certainly complicated structures; the study of their 'phrenology' is one important facet of the projected CRAF mission (Neugebauer and Weissman 1989), in which a spacecraft will remain in the vicinity of a comet for a number of years observing its changing activity, and (it is hoped) will attempt an *in situ* analysis of its crust.

Cometary activity has recently been identified on the Saturn orbit crossing object Chiron (Luu and Jewitt 1990). This is an interesting observation. On the one hand, it extends the size range in which comets are

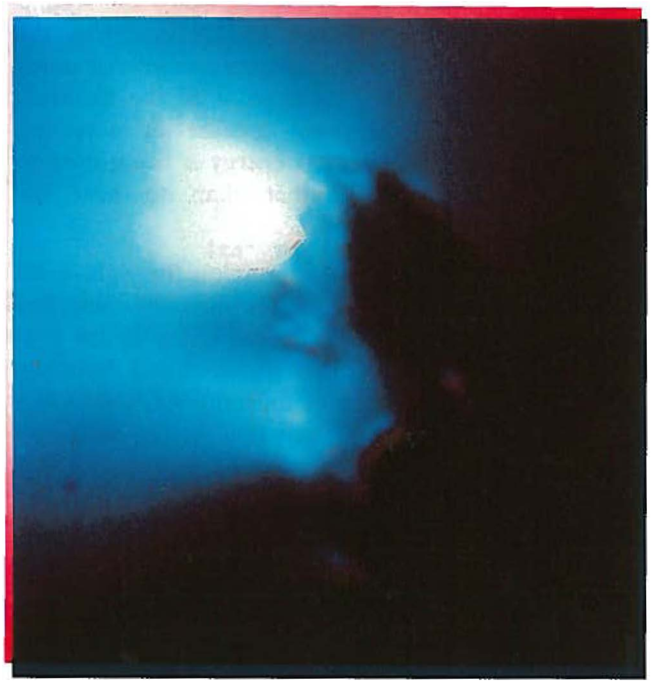

Figure 2. Composite image of the nucleus of Comet P/Halley, synthesis from several images taken with the Halley multicolour camera (HMC) on Giotto. The dark side of the nucleus is silhouetted against the light scattered by dust. Note the bright jets of dust (Keller *et al.* 1986).

known to exist to nearly 200 km; on the other hand, it poses the interesting question of the nature of the volatile material responsible for what appear to be sporadic bursts, since at the heliocentric distance where activity has been observed (at least about thirteen times the Earth's), water is quite definitely excluded as the agent.

Finally, it turns out that the cometary atmosphere tends to be accelerated as it evaporates from the nuclear surface. This occurs because any gas has a potentially useable store of energy in the form of the random translational motion of its constituent particles as well as the rotational and vibrational energy of molecules. The extraction of this energy and its transformation to produce directed flow is in itself an interesting fluid dynamics problem whose solution is different in different circumstances (rocket engines (Anderson 1990), the solar wind (Parker 1963), cometary atmospheres (Wallis 1983)); nevertheless, whatever the precise means by which the conversion occurs, one can understand that the transformation of a random thermal motion into a directed one must be accompanied by an acceleration. In the limiting case one can think of eliminating all the degrees of freedom of the molecules; moreover, expansion leads to a transfer to the directed motion of the work done by the pressure force. These two factors together can generate a directed velocity of $(14kT/\mu m_p)^{1/2}$ in the case of triatomic molecules such as water. At 200 K, this gives a directed velocity of a little over $1\ \mathrm{km\ s^{-1}}$. This is of course a very rough estimate: at cometary temperatures, the vibrational energy levels are unlikely to contribute significantly (Delsemme and Miller 1971), and the temperature of the gas itself is hardly likely to be the 200 K of the cometary surface; nevertheless, it is amusing to note that measurements of the expansion velocity of the atmosphere of Halley's comet made by Krankowsky *et al.* (1986) gave just $0{\cdot}9\ \mathrm{km\ s^{-1}}$. In what follows we shall round this figure to $1\ \mathrm{km\ s^{-1}}$.

Once formed, the cometary atmosphere is subject to a number of physical effects which in principle interact, and it is far from simple to find its detailed structure in any way other than through the numerical solution of many coupled equations (see for example Ip and Mendis (1976) or Schmidt *et al.* (1988)). However, the scales (temporal and spatial) of many of the phenomena are so different that to a first approximation many of the principal effects involved can be handled separately.

The characteristic appearance of comets close to the Sun is not that of a fuzzy ball, but rather that of a head and a long tail, as we can see from figure 1. Moreover, spectroscopic observation shows certain of these gases to be ionized. The Sun is responsible for both of these features, through its radiative and corpuscular emissions; this is the subject of the next few sections.

3. Interaction of a cometary atmosphere with solar radiation

At the nominal distance d of the Earth, the solar flux, given by $F_\odot/4\pi d^2$, is equal to $1{\cdot}4 \times 10^3\ \mathrm{W\ m^{-2}}$. A small fraction of this flux is at the very short wavelengths capable of ionizing cometary material; the fraction does vary as a function of solar activity but we shall take no account of this here. Ionization is a function of photons; as a rough average, the solar photon flux shortward of 1000 Å at the Earth's orbit is $\Phi_\odot \approx 3 \times 10^{14}$ photons $\mathrm{m^{-2}\ s^{-1}}$.

3.1. *Ionization frequency*

If the cross-section for ionization is σ_{ph}, the frequency with which molecules are ionized is given by $\Phi_\odot \sigma_{ph}$. The ionization cross-section is necessarily smaller than the geometrical cross section which would correspond to the Bohr radius; a conventional figure often used is $10^{-21}\ \mathrm{m^2}$. This leads to an ionization frequency of $3 \times 10^{-7}\ \mathrm{s^{-1}}$.

This estimate assumes that a negligible number of photons are actually removed from the incident radiation. This is not true throughout the entire cometary atmosphere, but we can find the region where the assumption is reasonably valid in the following way.

At a distance r from the cometary surface, the number density n of neutral particles in an atmosphere expanding spherically at velocity v is given by:

$$n = \frac{Q}{4\pi v r^2}, \tag{18}$$

assuming this time that the degree of ionization is small; Q is as before the total emission rate at the surface.

Consequently, the mean free path of photons λ_{ph} is in this case given by:

$$\lambda_{ph} = \frac{1}{n\sigma_{ph}} \tag{19}$$

$$= \frac{4\pi v r^2}{Q\sigma_{ph}}. \tag{20}$$

Ionization will remove a negligible number of photons if $r \ll \lambda_{ph}$, thus if:

$$r \gg \frac{Q\sigma_{ph}}{4\pi v} \tag{21}$$

$$= 8 \times 10^4\ \mathrm{m}, \tag{22}$$

using the nominal value of $Q = 10^{30}\ \mathrm{s^{-1}}$. Therefore, to all intents and purposes, beyond about a hundred kilometres from the cometary surface the ionization frequency is given simply by $\Phi_\odot \sigma_{ph} \approx 3 \times 10^{-7}\ \mathrm{s^{-1}}$.

3.2. *Ionization structure*

Let us continue to suppose that the cometary gases are expanding with spherical symmetry. At a distance r, the change in the number of ions due to ionization (but neglecting recombination) in a shell of thickness Δr is given by $4\pi r^2 \Delta r(n\Phi_{\odot}\sigma_{ph})$; this change is equal to $\Delta(4\pi r^2 n_i v)$, where n_i is the local ion density. Equating these terms, assuming that $n \propto 1/r^2$ and taking a constant expansion velocity v, a little elementary manipulation leads to:

$$\frac{n_i}{n} = \frac{r}{v/\Phi_{\odot}\sigma_{ph}} \tag{23}$$

One can see from this expression that neutral particles dominate at distances such that:

$$r \ll \frac{v}{\Phi_{\odot}\sigma_{ph}} \tag{24}$$

$$\approx 3 \times 10^6 \text{ km.} \tag{25}$$

Beyond this distance, the degree of ionization will be increasingly important, and the gas will reveal itself through emission related to high order transitions and recombinations. We have taken no account of the latter, but it is easy to understand that their effect would be in principle to extend the region where neutral particles dominate to distances farther from the nucleus; in fact, for the particular case of Halley's comet at the Earth's orbital distance, the inclusion of recombination does not significantly alter the conclusions.

Be that as it may, one can see that in certain spectral regions, such as the ultra-violet, comets will appear as enormous structures in spite of the very small size of the core. As an example, hydrogen Lyα emission extends out to typically ten million kilometres (Brandt and Chapman 1981).

A few words on the overall ionization structure of the cometary atmosphere might be in order here. Schematically, it resembles that of a planetary atmosphere, in the sense that the total particle density decreases outwards, while the intensity of ionizing radiation decreases towards the surface. In the case of our nominal cometary parameters, it is easy to show that the ion density close to the cometary surface is vanishingly small, because the atmosphere is very thick; moving outwards, the ionizing flux rises and the neutral particle density falls, so that the ion density, which is essentially found from the product of these two rising and falling functions, first rises, reaches a maximum and finally at sufficient distances from the surface, falls. One might well expect the maximum to occur in the general region of the value of equation (22), thus at low altitudes in the range of, say, the tens of km, rather than, say, in the thousands.

We note that this ionization maximum is well within the region where the overall degree of ionization is still low; thus, since $n \propto 1/r^2$, the ion number density sufficiently far from the maximum is found from equation (23) to vary as $1/r$. One might naïvely expect this variation to continue for the several million kilometres in which the neutral particles dominate; the significance of this will emerge shortly.

4. Interaction of a cometary atmosphere with the sun's corpuscular emission

The Sun is not only a source of radiation, but also of a flux of particles, generally referred to as the solar wind. This wind is highly ionized, and to a first approximation may be thought of as a flux of protons and electrons; it transports the solar magnetic field outwards throughout the solar system. The particles and the magnetic field can interact with the gaseous envelopes of planetary bodies – one can, for example, think of the solar wind as impinging on an atmosphere, whose pressure will then oppose the flow.

A small, but non-trivial, aside is in order here. For two media to interact strongly, the mean free path for collisions between their particles must be small with respect to the smaller of the scales of the two media.

Now, at the Earth's orbit, the density of the solar wind is of the order of 10^7 protons m^{-3}; taking the collision cross-section as corresponding to the Bohr radius, the mean free path for collisions of the solar wind particles with themselves is something like 10^{13} m, a figure approaching the size of the solar system itself. Of course, the solar wind is composed of charged particles, whose collision cross-section is rather larger, and at the temperature of the solar wind ($\leqslant 10^5$ K) turns out to be $\approx 10^{-18}$ m^2; this gives a mean free path of about 10^{11} m, smaller than before, but still very large! From this one might conclude that hydrodynamic type calculations (and in particular the very notion of pressure) are strictly excluded for the solar wind on scales significantly smaller than the solar system.

This type of argument neglects the effect of the solar magnetic field, whose value (at the Earth's orbit) is about 10^{-8} T. Charged particles gyrate in a field; the radius of gyration of, for example, the protons in the solar wind is somewhat smaller than 100 km, and it is this scale, rather than the *bona fide* mean free path, which determines the applicability of the hydrodynamic approach for the mutual interaction of charged particles – in this sense, so long as the solar wind is embedded in a significant magnetic field, its behaviour can for many purposes be assimilated to that of a fluid.

Consider now the neutral particles surrounding a comet. Their density varies with distance from the nucleus (see equation (18)); at distance r, the mean free path for the mutual interaction of neutral particles is at most (again assuming a cross-section given by the Bohr radius) $r^2/10^6$ m, so that hydrodynamic calculations for the neutral component should be invalid beyond a distance $r_{\rm lim}$ given by:

$$r_{\rm lim} = r_{\rm lim}^2 \times 10^{-6}, \tag{26}$$

that is, beyond about 1000 km. Thus, except for regions very close to the cometary surface, one should not be able to treat the neutral component as a fluid.

However, the cometary environment does contain an ionized component; the interaction cross-section for the mutual interaction of charged molecules is somewhat larger, giving a limiting distance of about 30 000 km; the cross-section for interaction of neutral molecules with ions is also rather larger than that given by a simple interpretation of the Bohr radius and turns out to be in practice comparable to that of charged particles among themselves. Thus, out to a few tens of thousands of kilometres, one can think of the mixture of ions and neutral particles as making up a single fluid. Since out to this distance there are many more neutral particles than ions, one concludes that the global motion of the ions will be controlled by that of the neutral particles.

Finally, the cross-section for the interaction of protons with neutral molecules is expected to fall somewhere in between that based on the Bohr radius and that of neutral molecules interacting with ions; beyond several thousand kilometres from the cometary nucleus, it should not be legitimate to treat the interaction of the solar wind with the neutral particles in the cometary atmosphere as the collision of two fluids.

However, the solar wind and the charged component of the cometary environment meet in the presence of a magnetic field; as we emphasized above, this enables their interaction to be treated in a way not unlike that of the collision of two opposing flows. It is then interesting to see whether there exists a region where their pressures balance, since such a region will form an interface between interplanetary and cometary conditions.

The dynamic pressure (sometimes referred to as the ram pressure) of the solar wind is given by $n_{\rm wind} m_p v^2{}_{\rm wind}$, where $n_{\rm wind}$ and $v_{\rm wind}$ are respectively the number density and velocity of the solar wind; putting the velocity of the solar wind as 400 km/s, its typical value at the Earth's orbit, the dynamic pressure (which we shall subsequently refer to as $P_{\rm wind}$) turns out to be 3×10^{-9} Pa.

We have seen that out to about 3×10^4 km, the charged component of the cometary atmosphere is 'dragged' along by the neutral particles; the pressure which opposes the solar wind is thus the dynamic pressure of the flow of neutral particles, i.e. $n\mu m_p v^2$.

Equilibrium occurs at a distance $r_{\rm eq}$:

$$P_{\rm wind} = n_{\rm wind} m_p v_{\rm wind}^2 = n\mu m_p v^2 \tag{27}$$

$$\frac{Q\mu m_p v^2}{4\pi v r_{\rm eq}^2}. \tag{28}$$

The distance $r_{\rm eq}$ from the cometary nucleus where pressure equilibrium obtains is approximately 3×10^4 km; we note in passing that it is reassuring that this value is consistent with the region in which the ion component is effectively dragged along by the neutral particles. Schematically, one can say that this distance separates two regimes, one where purely cometary phenomena dominate, and one where conditions are increasingly influenced by the solar wind. We emphasize that these two régimes concern essentially the charged component of the cometary environment; since the neutral component dominates, it will hardly be affected by the behaviour of the ions, while in its interaction with the solar wind, analyses based on notions such as 'pressure' have become inappropriate well before 3×10^4 km.

5. Interaction of a cometary atmosphere with the Sun's magnetic field

So far, the magnetic field has served only to magically transform a medium which should by all rights be handled as a set of rarely colliding particles into one which can be analysed as a fluid; this has allowed us to establish the existence of distinct zones of influence in the cometary environment.

In fact, the presence of the interplanetary magnetic field has a much more profound influence, which we shall now examine; this will give fresh insight into the significance of these zones.

The solar wind is a highly ionized and rarefied outflow of material from the sun and its electrical conductivity turns out to be extremely high; the Sun, source of the wind, is also associated with a magnetic field.

Changing a magnetic field within a conducting material generates currents whose overall effect is to oppose the change; the higher the conductivity, the more difficult it is to create a change. The motion of a plasma through a magnetic field is a process of this general type: the currents generated tend to hinder the relative 'slippage' of the lines of force and the medium, and if the conductivity is sufficiently high, as for example in the case of the solar wind, the lines become strongly coupled to the medium, a condition sometimes referred to as 'frozen in'.

The notion of a frozen-in field should be taken with a pinch of salt. It is often more profitable to think in terms of the diffusion of the lines of force through the medium;

in this sense, a 'frozen in' field is merely one whose lines of force take a long time to diffuse across the medium compared with some characteristic time scale related to changes in the medium. Following Jackson (1975), one may write the diffusion time τ_{diff} over a distance L in a medium of electrical conductivity Γ as:

$$\tau_{\mathrm{diff}} = (\Gamma\mu_0)L^2 \tag{29}$$

$$= \frac{n_e e^2 \mu_0}{m_e \nu_e} L^2 \tag{30}$$

$$= \frac{n_e e^2 \mu_0 \lambda_e}{m_e v_e} L^2, \tag{31}$$

where ν_e, λ_e and v_e are respectively the collision frequency of the electrons, their mean free path and their characteristic thermal velocity.

Taking the example of the solar wind, during the time τ_{diff} the medium will move through the distance $\mathscr{L} = v_{\mathrm{wind}}\tau_{\mathrm{diff}}$; if $\mathscr{L}/L \gg 1$ the magnetic field is 'frozen'. In the solar wind, we have seen that the collisional mean free path is at least 10^{11} m, the temperature of the electrons is a few times 10^5 K and the density about $10^7\ \mathrm{m}^{-3}$; from this we find that:

$$\frac{\mathscr{L}}{L} = \frac{n_e e^2 \mu_0 \lambda_e}{m_e v_e} v_{\mathrm{wind}} L \tag{32}$$

$$\approx 10^4 L. \tag{33}$$

This will be greater than 1 for scales exceeding one tenth of a millimetre; thus for essentially any astrophysically interesting scale in the interplanetary medium and in the absence of other media, the magnetic field will be carried along by the solar wind. Note that the criterion leaves a considerable margin: even in media which are rather less perfectly conducting than the solar wind, the magnetic field will tend to be 'frozen' on astrophysically interesting scales.

When the magnetic field encounters an electrically conducting obstacle which opposes the flow of the solar wind, a similar problem will arise: the 'moving' lines of force may not be able to diffuse through the obstacle as fast as they are swept by it; if the obstacle is massive and cannot be significantly affected by the momentum of the solar wind (the usual case) the penetration of the magnetic field upstream of the obstacle will be hindered, while the field far from and to the sides of the obstacle will continue to be swept along – the field lines will tend to be 'draped' around the obstacle, in front of which the field will tend to accumulate.

The cometary atmosphere is not a rigid body; its ionization is quite sufficient to ensure the 'freezing in' of the magnetic field, but in its outer regions, the ion pressure is insufficient to stop the field being carried along by the solar wind. Thus, as the solar wind with its embedded magnetic field sweeps in, the ions in the outer regions of the cometary atmosphere will tend to be carried along with it; in this way, the magnetic field can remain 'frozen' to both the wind and the cometary atmosphere.

A fundamental quantity characterizing a magnetic field of value B is its energy density, given in a vacuum by $B^2/2\mu_0$, where μ_0 is the permeability of free space. The mechanical interaction of a magnetic field of value B with a plasma can be thought of in terms of two convenient quantities (Cowling 1976):

- The magnetic 'pressure' P_B:

$$P_B = \frac{B^2}{2\mu_0}. \tag{34}$$

This 'pressure' behaves in its effects on a plasma essentially just like a gaseous pressure, that is, its gradient represents the force per unit volume exerted on the charged particles of the plasma.

- The magnetic 'tension' T_B:

$$T_B = \frac{B^2}{\mu_0}. \tag{35}$$

This 'tension' acts along the lines of force and as defined above represents a force per unit area perpendicular to them: just as in the case of a stretched string, restoring forces perpendicular or parallel to the lines of force appear when the latter are, respectively, deformed or stretched. An interesting by-product of magnetic tension is the possibility of propagating deformations along the field direction: such waves are called Alfvén waves, their velocity v_{alf} being given by:

$$v_{\mathrm{alf}} = \left(\frac{T_B}{\rho}\right)^{1/2} = \left(\frac{B^2}{\rho\mu_0}\right)^{1/2}. \tag{36}$$

A detailed discussion of the 'mechanical' role played by a magnetic field acting on a plasma would be out of place here, and the reader is referred to Cowling (1976).

5.1. *Penetration of the interplanetary magnetic field into the cometary environment*

Consider now the solar wind sweeping round a cometary atmosphere. Upstream of the flow the magnetic field, unable to penetrate as rapidly as the wind sweeps by, builds up, and the field lines bend round; one can think of the upstream field as a cushion between the incoming solar wind and the expanding cometary gases. In this sense, the global pressure equilibrium will still be between that of the solar wind and the neutral molecules of the cometary atmosphere, as in section 4; if we ignore the fact that as it penetrates the outer regions of the atmosphere the solar wind picks up some cometary ions (thereby modifying its dynamic pressure), the pressures will again be in equilibrium at a distance of $r_{eq} \approx 3 \times 10^4$ km.

This is the position of the interface (identified in section 4) between the purely 'cometary' zone of influence and the 'interplanetary' region; we now see that it also separates an essentially magnetic field free cavity from one where the field rises gradually from its normal interplanetary value to a maximum value of B_{max} at the interface itself:

$$\frac{B_{max}^2}{2\mu_0} = P_{wind} = 3 \times 10^{-9}, \tag{37}$$

which gives a field of about 10^{-7} T, roughly ten times the interplanetary value.

5.2. *The magnetic tail*

Consider now in a little more detail what happens to an interplanetary tube of force. Far from the comet, over distances of tens of millions of kilometres, such a tube is essentially straight; as the wind sweeps over the cometary environment, the tube will bend round and take up a kind of U-shape, the ends of the 'U' ultimately bending round again into the general direction of the interplanetary field sufficiently far behind the comet. A magnetic tail will thus trail the comet. Over the lateral extent of the tail, one can see that the tubes of force have been extended against their tension, compared with their state in the absence of the comet: this constitutes an increase of magnetic energy density, whose source is, in the final analysis, the kinetic energy density of the solar wind. Since the latter is limited, the tubes cannot be stretched beyond a certain distance behind the cometary head; we shall call this distance L_{max} and it corresponds to stretching the tubes by $2L_{max}$.

Consider a length L of a tube of force in which the field is B. If we stretch the tube while conserving its volume and the magnetic flux, $B \propto L$. Thus, stretching the tube from a length L_0, when the field was equal to B_0, to $2L_{max}$ requires an energy density equal to $B_0^2(2L_{max})^2/2\mu_0 L_0^2$; the kinetic energy density of the solar wind is $n_{wind} m_p v_{wind}^2/2$, whence:

$$\frac{B_0^2(2L_{max})^2}{2\mu_0 L_0^2} = \tfrac{1}{2} n_{wind} m_p v_{wind}^2, \tag{38}$$

so that:

$$\frac{(2L_{max})^2}{L_0^2} = \frac{n_{wind} m_p v_{wind}^2 \mu_0}{B_0^2} \tag{39}$$

In the spirit of this estimate, B_0 is of course just the component of the unperturbed interplanetary magnetic field perpendicular to the motion of the solar wind as it impinges on the comet, and L_0 the lateral width of the magnetic tail of the comet. The interplanetary field has a spiral structure centred on the Sun, and at the Earth's orbital distance its direction is roughly 45° with respect to the radius vector of the Sun; since the value of the field is 10^{-8} T, equation (39) evaluates to:

$$\frac{(2L_{max})^2}{L_0^2} \approx 100. \tag{40}$$

We have already found an inner limit to the presence of magnetic field within the cometary environment in the forward hemisphere – the distance $r_{eq} \approx 3 \times 10^4$ km; twice this distance delimits the lateral extent of a volume behind the comet where the field is also absent. In this sense, we can imagine a kind of 'U'-shaped surface around the comet where the field has a maximum value of $B_{max} \approx 10^{-7}$ T and within which it is essentially absent; however, the volume in which the field is significantly different from its interplanetary value is much larger than this. To have a rough idea of how far around a comet the field is seriously perturbed, let us imagine the unrealistic but convenient situation of an initially uniformly expanding cometary atmosphere encountering the solar wind for the first time; at some distance from the head, the outward momentum density of the cometary ions will be comparable to the inflowing momentum density of the protons in the solar wind, which will therefore be slowed down. Since the magnetic field is frozen into the solar wind, the magnetic field in this region will become significantly enhanced with respect to its ambient interplanetary value. The position r_0 of this zone in front of the comet is easily found by noting that:

$$\text{momentum density of the solar wind} = n_{wind} m_p v_{wind}, \tag{41}$$

$$\text{momentum density of cometary ions} = n_i \mu_i m_p v_i, \tag{42}$$

where n_i, μ_i and v_i are, respectively, the cometary ion density, ion molecular weight and flow velocity. Now, we have already found an expression for the ion number density as a function of the neutral number density (equation (23)): in this expression, we should of course use the ion velocity in place of the velocity v. We also know how the neutral density varies with distance from the nucleus (equation (18)). Combining these expressions and substituting in equation (42), we find immediately:

$$\text{momentum density of cometary ions} = \frac{\mu_i m_p \Phi_\odot \sigma_{ph} Q}{4\pi v r}. \tag{43}$$

This is equal to the momentum density of the solar wind (equation (41)) at some distance r_0, which is easily seen to be:

$$r_0 = \frac{\mu_i \Phi_\odot \sigma_{\mathrm{ph}} Q}{4\pi v n_{\mathrm{wind}} v_{\mathrm{wind}}} \tag{44}$$

$$\approx 10^5 \text{ km}, \tag{45}$$

using our canonical values. The scheme we have used to obtain this result is a gross simplification, even a distortion of the actual situation: since the motion of the cometary ions is affected strongly by the magnetic field which is being carried in by the solar wind, there will ultimately be very few ions actually moving out at these distances, most being swept in with the solar wind. This, however, hardly alters the final answer.

The characteristic width of the magnetic tail, the quantity we referred to previously as L_0, is just twice the value of r_0. With this result, and the expression for the ratio of the length of the magnetic tail to its width (equation (40)), we find the length of the magnetic tail to be just 10^6 km.

This calculation contains the hidden (or implicit, depending on one's point of view) assumption that the state of the interplanetary medium in the vicinity of the comet remains unaltered during the period of time required to establish the magnetic tail. This need not be so, since the interplanetary magnetic field is in reality far from the simple spiral we suggested above, and the ambient medium is full of perturbations related to violent phenomena on the Sun. Nevertheless, the most important changes are essentially inversions in the direction of the magnetic field, which are known to occur on a time scale of roughly one week: at the velocity of the solar wind, this corresponds to a spatial scale of several hundred million kilometres. It is not clear how the magnetic tail of a comet will be affected by a change in the direction of the interplanetary field – for example, the tail could be destroyed until the new direction is established – but whatever happens, it will only happen about once a week, and will hardly affect the production of the tail. It is hard to understand how minor perturbations of the interplanetary medium could affect the global structure of the cometary environment

5.3. *Tracing the cometary magnetic environment*

Short of sprinkling iron filings around a comet, or some equivalent hi-tec procedure such as sending a swarm of spacebourne magnetometers to explore the region around a comet, we have no way of directly sensing the structure of its magnetic field. However, nature does rather kindly provide us with a sort of tracer: the cometary ions will tend to be trapped within the enhanced field around the comet, and their emission shows us how the lines of force are distributed. This is the origin of the characteristic ion tail that many comets exhibit.

There are, however, a few points of 'detail' which make this tracer less than ideal:

- ions tend to recombine;
- the ions would have to fill up completely the cometary flux tubes for the whole field to be materialized;
- the ions emitted directly towards the tail will naturally fill up the region in which the field is absent: these ions will therefore *not* be tracers of the field;
- the ions which are injected into the field come essentially from those which are emitted in the forward hemisphere; however, since their density decreases with distance from the comet, the ion distribution will decrease rapidly outwards from the critical surface at $r_{\mathrm{eq}} \approx 3 \times 10^4$ km;
- to have any kind of meaningful trapping of ions, the scale length of the trapping must be significantly larger than the ion gyromagnetic radius; this need not always be so, since many of the scale lengths are functions of the heliocentric distance of the comet.

In this sense therefore, the magnetic tail length we estimated in the previous section represents the upper limit of the visible length of an ion tail.

6. The cometary environment as it really is

The results of the experiments on the 'space armada' which visited Halley's comet in 1986 illustrate very nicely many of our theoretical conclusions about the general distribution of the neutral particles and ions in front of a comet (details can be found in a special issue of Nature (1986)).

- Close to the comet, that is, within several thousand kilometres of the surface:
  - the ion density fell as $1/r$;
  - the flow velocity of the ions was about 1 km s^{-1} outwards from the surface;
  - the particle temperature was in the general region of 200 K;
  - the magnetic field was essentially zero.
- From about several thousand to several tens of thousands of km, the situation was extremely merdicque:
  - the ion density rose, then fell;
  - the ion flow velocity fluctuated about zero;
  - the ion temperature rose abruptly;
  - the magnetic field rose rapidly to a maximum value of a little under 10^{-7} T.

- Beyond several tens of thousands of km:
  - the ion density fell as $1/r^2$, out to about a hundred thousand kilometres;
  - the ion flow took on the direction of the solar wind, and its value rose with distance from the comet;
  - the ion temperature continued to rise, but rather more slowly than in the intermediate region;
  - although the magnetic field had large oscillations, its average value fell gradually, tending towards the interplanetary value at roughly 10^5 km.
- Out to at least 4×10^4 km, the density of the neutral molecules (whose composition was dominated by water) varied roughly as $1/r^2$ and their velocity, of the order of $1\ \mathrm{km\ s^{-1}}$, was away from the cometary nucleus; moreover, ionized molecules of presumably cometary origin were detected at distances of several million kilometres – whatever the ionization mechanism, this suggests that the solar wind does not represent a barrier to the neutral particles.

The Halley armada did not pass through the magnetic tail, whose characteristics we have been able to deduce only from remote sensing of the ion component; at the heliocentric distance of the Earth, the visible length was roughly 10^7 km; the visible width was something like 10^5 km.

It is far from obvious how to relate the results of remote sensing to our estimates, since the observed parameters depend on the way the images were obtained, on the direction of the tail relative to the line of sight etc.; one must remember that the observations are integrated over the line of sight.

To date, the only *in-situ* studies of a cometary tail were made on board ICE, a 'recycled' spacecraft which, after spending most of its life investigating the interplanetary medium in between the Earth and the Moon (where it was called ISEE) was renamed and sent into the tail of comet Giacobini–Zinner towards the end of 1985. As with Halley's comet, the encounter occurred at the heliocentric distance of the Earth. There (*Science* 1986):

- the magnetic field was found to be absent from a region whose width was about 10^3 km; this region was particularly rich in ions;
- the magnetic field was effectively 'draped' around the nucleus, suggesting the 'U'-shape of which we spoke above; the maximum of the field, at the edges of the ion-rich and field-free cavity, was a little less than 10^{-7} T;
- the field was effectively enhanced with respect to its interplanetary value out to a distance of about 5000 km from the axis of the tail.

It is important to note here that Giacobini–Zinner is a rather quiescent comet, with an outgassing rate about thirty times smaller than the 'canonical' value of Q used in our calculations; most of the spatial scales are direct functions of Q, and taking this into account, we see that comet Giacobini–Zinner actually fits our expectations as well as Halley's comet.

7. Dirty hair

We have so far visualized the cometary head as surrounded by and trailing nice clean strands of magnetic field, decoratively highlighted by gleaming ions.

This may be true for a few comets; it is certainly an incomplete description of most.

The cometary environment is in fact strongly contaminated by a component conventionally referred to as dust – grains of material considerably less volatile than the 'ices' we have spoken of so far (or which for one reason or another were ejected before being evaporated). A part of this dust is made visible by the scattering and reflection of sunlight; the size of these grains is thus in the same general range as the wavelength of visible light – we shall take $0{\cdot}5\ \mu$ as a convenient characteristic radius. Smaller grains do exist; their presence was at best surmised before the Giotto and VEGA missions, which managed to detect them directly. There are also rather larger 'stones'.

We shall limit our discussion to the $0{\cdot}5\ \mu$ grains.

7.1. *Why the cometary environment should be dust free*

We saw in section 2 that the surface of a comet reached a temperature of about 200 K; this allowed us to estimate the largest nucleus which could generate a very large head of atomic hair.

The thermal velocity of the dust grains will surely not be significantly higher than that which corresponds to this 200 K (it will certainly be lower); using equation (14) for the maximum radius of a body which can allow particles to escape from it, substituting 200 K for the temperature, $1000\ \mathrm{kg\ m^{-3}}$ for the density of the cometary head and that of the grains themselves, taking the dust grain radius as $0{\cdot}5\ \mu$, we find immediately that grains of the type which are observed at large distance from typical comets cannot escape from bodies larger than 4 m! Even this is a considerable overestimate, since the dust is certainly not in thermal equilibrium at 200 K.

In brief, dust grains left to their own devices are simply moving too slowly to do anything interesting.

7.2. *Why comets do have dust in their hair*

In fact, the dust grains are not left to their own devices: they are acted on by the fast moving gas molecules, whose viscous drag accelerates them to high velocities.

In section 2, we found (from equation (9)) that the characteristic thermal velocity $\langle v \rangle$ of the gas molecules leaving the cometary nucleus is $\approx 500 \text{ m s}^{-1}$; we found also (equation (12)) that they are emitted at a rate Z of about 4×10^{21} molecules $\text{m}^{-2} \text{ s}^{-1}$.

Writing the cross-section of a (hypothetically spherical) dust grain as πr^2_{grain}, and assuming that the velocity $\langle v \rangle$ corresponds to the mass flow of the escaping gas, the force F exerted by the molecular flow on a dust grain at the cometary surface can be written as:

$$F = Z\pi r^2_{\text{grain}} \mu m_p \langle v \rangle. \tag{46}$$

To ensure that a grain of density ρ can escape from the cometary nucleus of radius R and density ρ, this force should be greater than the gravitational attraction at the surface $(\frac{4}{3}\pi\rho r^3_{\text{grain}})(\frac{4}{3}\pi\rho RG)$, whence after some simplification and rounding:

$$R < \frac{Z\mu m_p \langle v \rangle}{6Gr_{\text{grain}}\rho^2} \tag{47}$$

$$= 3 \times 10^5 \text{ km}. \tag{48}$$

The dimensions of cometary nuclei being at most several hundred kilometres, we see that the viscous drag of the escaping molecular gas enables the dust to escape as well; moreover, the effect is so strong that much more massive dust grains – 'stones' – can escape along with the finer material, creating a very real danger for any spacecraft so foolhardy as to approach too close. Indeed, images from the Giotto spacecraft did show a very hostile environment in the immediate vicinity of the comet, and both the VEGA and Giotto spacecraft were seriously damaged during their flyby.

7.3. *What happens to the dust*

As the dust moves outwards from the nucleus, the viscous drag diminishes, in contrast to the solar wind and radiation flux, which at a sufficient distance will be the dominant influence. We know that the former produces a pressure of 3×10^{-9} Pa; the radiation pressure of the solar flux ($1{\cdot}4 \times 10^3 \text{ W m}^{-2}$, as given in section 3) is essentially $1{\cdot}4 \times 10^3 c^{-1}$, which comes to $\approx 5 \times 10^{-6}$ Pa. Thus, in practice, the grains are principally acted upon by the pressure of the solar radiation and the Sun's gravitational field.

Schematically, we will take the grains as being 'launched' from the cometary nucleus with a velocity of 500 m s^{-1}; ignoring the subsequent action of the gas, the grains emitted towards the sun will be decelerated by the radiation pressure P_{rad} at the rate γ:

$$\gamma = \frac{3P_{\text{rad}}\pi r^2_{\text{grain}}}{4\pi\rho r^3_{\text{grain}}} \tag{49}$$

$$\approx 7 \times 10^{-3} \text{m s}^{-2}. \tag{50}$$

Their initial velocity v_{initial} will be annulled at a distance D:

$$D = \frac{v^2_{\text{initial}}}{2\gamma} \tag{51}$$

$$\approx 2 \times 10^4 \text{ km}, \tag{52}$$

which is somewhat smaller than the observed sunward extent of the surrounding dust: in fact our calculation is an underestimate, since we have taken no account of the very broad range of grain sizes, and as we noted at the beginning of this paper (section 2), the gas emitted by the comet is accelerated from ≈ 500 m/s to ≈ 1000 m/s, which will impel the dust grains to rather higher velocities than the value we used above.

The radiation pressure will tend to push the dust behind the comet, forming a dust tail; however, this tail will neither be parallel to the ion tail, nor will it be straight.

To understand this, we recall first that the orbital velocity of a comet at the heliocentric position of the Earth is in the tens of kilometres per second. Consider for simplicity a comet on a circular orbit with the Earth's orbital radius; it will be moving at 30 km s^{-1}.

Now, the ion tail is constrained by the trailing magnetic field, which is formed at the velocity of the solar wind, i.e. $\approx 400 \text{ km s}^{-1}$. Thus, as the comet continues on its orbit, the magnetic tail which channels the ions is able to adjust its direction to be constantly almost aligned along the radius vector to the Sun.

Once the dust grains have left the immediate vicinity of the comet and have become significantly influenced by the radiation pressure they will travel along individua heliocentric orbits. However, these orbits will correspond to a central attraction which is less than that of the Sun since radiation, which varies also as the inverse square of the distance, acts in the opposite direction; thus, as each grain leaves the influence of the comet, it will take up an orbit which is tangential to the direction of motion of the comet at its instantaneous position, but with an eccentricity >0. The eccentricity will depend on the acceleration induced by the radiation pressure: the smaller the grain, the greater the acceleration and therefore the greater the eccentricity of the corresponding orbit–the orbits of sufficiently small grains will in fact be open. Thus, as the comet continues on its orbit, it will gradually separate from its emitted grains which, being on more open orbits will have a lower angular velocit about the Sun and will lag behind: the locus of the point reached by the grains emitted during a certain period o time will be a curve, which will be neither aligned alon a radius vector, nor be straight.

To clarify these ideas, consider our 'canonical half-micron grains. The acceleration induced by radia tion pressure (equation (50)) is very close to the gravitational acceleration induced by the sun (6×10^{-3} m s^{-2}) which will therefore be essentially annulled: such a grain moving initially with the comet will suddenly find itself free of all central forces, and will therefore continue in a straight line with the instantaneous value and direction of the cometary orbital velocity. Thus, one quarter of an orbit later, say, the grain will have moved a distance $\pi d/2$ in its original direction so that its direction with respect to the new radius vector of the Sun will be arctan $2/(\pi - 2)$; grains emitted at intermediate times will lie along a curved path passing from the comet to this grain, whose length will be somewhat greater than d. From these considerations, one can see that the locus of the grains which have not yet separated from the nucleus by a large distance will be closer in direction to the instantaneous radius vector than grains which are far away; the overall locus will resemble a spiral. In fact, a rotating garden sprinkler is not a bad way to visualize this particular situation.

The larger the grain, the smaller the acceleration induced by the radiation pressure, and so the closer the grain orbit will be to that of the comet itself. Consequently, dust tails are expected to have a kind of 'fan shape', in which grains are separated as a function of mass – in some sense, the dust tail of a comet is a (badly calibrated) mass spectrometer. The inner edge of the fan corresponds to relatively massive grains following the cometary orbit itself; the outer edge is rather poorly defined, since the radiation pressure on very small grains does not follow the simple scheme outlined above.

Dust tails would apparently extend to indefinite distances; in general, however, we will be able to observe directly only the densest part of the dust distribution and therefore that which is closest to the cometary nucleus. This is essentially what is shown in figure 1.

A few points enrich considerably the dynamics of dust tails:

- cometary orbits are generally rather elliptical and not circular; although the underlying idea remains unchanged, the details become more complicated.
- The dust grains are subject to a radiation force which acts not only in a radial direction, but also along their direction of motion, through the Poynting–Robertson effect. This adds a kind of viscous resistance to their motion; certain grains which would otherwise be ejected from the solar system fall instead into the Sun. Again, however, this makes the analysis more difficult, without changing the basic phenomena.

Note in passing that the smallest dust grains are in fact spread throughout the entire solar system and are ultimately lost to it; the heaviest will be distributed along orbits which follow approximately the comets which were their sources. If these latter orbits happen to cross that of the Earth, the particulate matter will at regular intervals enter our atmosphere and give rise to meteor showers (as shown dramatically in Figure 3). On the other hand, the smallest grains, which are everywhere, will tend to be swept up continuously by the upper layers of the terrestrial atmosphere, where they can be collected by high flying aircraft (and orbiting space platforms) for

Figure 3. A meteor shower, from a nineteenth century drawing. (A. Guillemin, *Le Ciel*, 1877; Observatoire de Paris, photo Counil).

analysis in the laboratory; while apparently a nice technique for doing cometary science 'on the cheap', we do not unfortunately know what fraction of the material thus analysed is intrinsically cometary in origin.

8. Some final comments

We have seen in this paper that a remarkable number of basic properties of the cometary environment can be reconstructed, even on a quantitative level, from an old illustration and some modern physics.

Of course, the calculations in this paper are of an indicative nature; they should (and have been) done in far more detail to convince oneself that these aspects of the cometary environment are really understood. Nevertheless, the rigorous analysis of a system whose infrastructure one has mastered, while important and even amusing, does not necessarily lead to important discoveries, and there is no great merit in complexity *per se*; what fundamental questions concerning comets remain to be answered?

8.1. *Fundamentally difficult questions*

We have made no attempt to even sketch one large class of phenomena: the chemical changes which occur as the cometary atmosphere expands under the influence of ionizing solar radiation. In fact, any such attempt would not only strain the readers' patience to the limit but would also multiply the length of this paper by an inordinate factor.

Cometary nuclei are not made exclusively of water molecules, but contain many other 'additives' such as carbon, nitrogen and sulphur combined into various molecules which ionize, interact, divide into radicals, exchange electrons and so on: the cometary atmosphere has the wherewithal for a particularly creative brand of cookery. At a recent count (see, for example, Schmidt *et al.* (1988)), the chemical reactions run to over a thousand and involve rather more than a hundred molecules. Clearly, this type of work is a marvellous field for numerical analysts (indeed, one suspects that the current limitation on the number of reactions is imposed more by the computer rather than anything else) and for molecular spectroscopists; however, while it is important to ensure that the lines observed are identified, and the chemical networks which produced them understood, one wonders whether any startling discovery about the atmosphere can ever be made in this way, since the parameters which go into the computer kitchen are so numerous that with sufficient ingenuity one can probably fit anything to anything, especially as many of the reaction rates are speculative.

A fundamental motivation for studying the cometary atmosphere has been to identify the elementary and molecular composition of the nucleus using remote sensing techniques which see only the atmosphere and not the nucleus which is after all its ultimate source; this is certainly a worthwhile motivation, but is the task realistic, in view of the complexity of the atmospheric chemistry? If an exotic molecule having, say, biological implications, is suggested by this work, will anyone in fact really believe it?

Dust grains are no easier to study, but for quite different reasons. The detailed dynamics of the dust around a comet is surely a question of summing appropriately all the forces (itself not an obvious task, but hardly fundamental). Remote sensing techniques (such as examining their colour in the way that astronomers do for asteroids) which rely essentially on the way the grains reflect solar light have probably yielded as much as one can hope to find without actually analysing the grains chemically and under a microscope; the only sure way to do this is via an *in situ* mission, equipped with suitable collectors and analysers, or by a sample return mission. Even then, analysing the grains for themselves is (with one possible proviso, see below) of limited interest; a currently fashionable trend is to consider the cometary grains as samples of interstellar material, which one has little hope of analysing directly in the near future, but which the cometary surface has been able to accumulate during the extensive time spent in the outer regions of the solar system.

The magneto-hydrodynamic environment which surrounds and trails behind a comet is a particularly rich source of difficulties. The flux tubes are under considerable strain, creating ideal conditions for the propagation of waves; the particle distributions are not equilibrium ones and their source is variable; the environment encompasses a very broad range of thermodynamic, magnetic and plasmic parameters; the medium is not even just a nice 'clean' plasma, but contains dust grains, which pick up charges, give them up and generally perturb even farther what is already an extremely perturbed situation!

Under these conditions, plasma waves and instabilities are legion so that the task of recognizing and classifying them has grown into a field of considerable importance. One would like in part to interpret the rich 'micro-structure' observed in cometary atmospheres and tails: plasma 'knots' which move, tails which change their shape, disappear and reappear, structures such as 'streamers' or the 'doubled' plasma tail one can see in the drawing of Donati's comet (and the only feature we made no attempt to explain!). It is amusing (but not necessarily significant) to note that the Alfvén velocity (see equation (36)) of transverse waves propagated along the field lines in the tail is in the tens of kilometres per second, just the kind of velocity with which features are observed to drift along the tail.

We have emphasized that to a large extent it is the solar wind which calls the tune of the magnetohydrodynamic environment; however, the solar wind is not constant, it has its own complex spatio-temporal structure and one would like to know just how this affects the appearance of comets. Such questions are extremely difficult to answer, even to attack, without the detailed and three-dimensional knowledge of the internal structure of a cometary atmosphere that could be furnished by an exploratory space probe; it is not even clear that the answers will emerge with such direct knowledge – after all, the terrestrial ionosphere has been under detailed, space-based observation for many years, and we can hardly claim to have mastered many of the subtleties. Are these questions, however, intrinsically fundamental? When we have answered them, will our understanding of the underlying physics be deepened, or will we have just attached names to particular structures and regions? Some apposite comments (in another, albeit related context) may be found in Montgomery (1983).

As if each of these individual problems were not sufficiently intractable taken in isolation, they all in fact interact.

8.2. *Difficult fundamental questions*

In the previous section, we highlighted a number of problems whose solution would clarify the structure of comets.

Comets might also give some clues allowing one to attack other kinds of question.

It is currently surmised that comets are a sample of the most primitive material of the solar system; if this is true, analysing their material will be the only way to begin to understand how the solar system was formed. This idea stems in part from their size and the fact that most comets spend much of their time in the outer reaches of the solar system; it is thus believed that their structure should not have altered significantly from the time of their creation. In this sense, the study of a cometary nucleus could yield astrophysical information unobtainable by any other means. Note however that similar hopes have at one time or another been entertained for most smallish bodies in the solar system. Flyby missions have dashed all these hopes: we have discovered a remarkable richness of ill-understood geological processes, and we have as yet seen no body which has maintained its original pristine state. And we already know that cometary surfaces, at least, are highly active and that much of the most volatile material will have left the surface of any comet we can visit in the near future: one will have to drill into the very deep interior to even have a hope of reaching 'primitive' material.

It is not impossible that basic physics and chemistry will benefit from cometary explorations.

- The dust component of a comet constitutes an enormous surface area, which is in constant interaction with the gaseous atmosphere; this is because there are many dust grains, and because each grain may have an extremely complex surface. Chemical reactions proceed in quite new ways in the presence of a surface; in particular, reaction rates which in the gaseous state would be vanishingly small can be important on a surface, as a consequence of trapping. Indeed, a currently fashionable model for the evolution of pre-biotic macromolecules requires the presence of mineral surfaces. At present, the surface chemistry of cometary dust grains is almost virgin territory, especially as we have little idea of the exact nature of their surface–for example, is it fractal?

- Just where do large molecules end and small grains begin?

- The gaseous cometary environment involves streams of material whose bulk velocity goes from supersonic to subsonic. In normally constituted fluids, shocks would be a normal feature; however, as we emphasized previously, much of the cometary environment is collisionless and we do not possess a proper theory for handling such problems. We have seen one way of 'patching up' the situation, by 'plugging in' the magnetic field and so extracting an effective mean free path much smaller than the real one; this works, but it is not really clear why. At present we lack a fundamental theory of collisionless fluids; comets are not of course the only example, but to the extent that they have different parameter régimes and different intrinsic structures to the others, they are worth studying. One might note in passing that so far, none of the cometary fly-by missions has produced clear evidence for a shock boundary of the type that a fluid-dynamicist would recognize.

- There is some feeling that all is not right with our understanding of the ionization mechanisms which operate in the inner part of the cometary atmosphere: the ionization may be stronger than all conventional methods can produce. A fundamentally new process was suggested some years ago (Alfvén 1954) in a quite different context; it is not clear how it would operate in practice in the cometary environment (or indeed anywhere), but at present that would seem potentially to be the medium where it is needed most and where it might be investigated.

8.3. *On received wisdom*

It is clear that little progress in cometary science can be expected without an *in situ* mission to a comet which

> "Past experience has shown that stepping up from remote observations to detailed laboratory studies on Earth doesn't merely sharpen our perception of a system—it totally changes our outlook [...] A striking example of this change in scientific perspective can be cited: the revolution in our knowledge of Earth's moon that occurred when samples of it were brought to Earth in 1969–72. In spite of the proximity of Earth and Moon, the amount that had been learned about the latter by remote observations prior to 1969 was really very small. Scientists in the 1960s argued about the meaning of such observational minutiae as oddly shaped craters ('dimple craters') and the photometric function of the lunar surface (evidence for highly anomalous behaviour of lunar dust?); debated whether the lunar craters were produced by impact or volcanism and whether the maria were lava flows, dust deposits, or dry lake beds; and speculated about the composition of the lunar crust: granite, andesite, basalt, ultramafic rock, or chondritic meteorites? The return of samples swept all this away in an instant [...] Most of the scientists who were vocal about the Moon in the 1960s were not heard of after 1969."

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Contemporary Physics, 1991, Volume 32, number 5, page 367

CORRIGENDUM

A plain man's guide to the cometary environment

L. M. Celnikier and N. Meyer

Contemporary Physics, Vol 32, No 2, pp. 73–88.

Owing to a printing error, some lines were unfortunately omitted from the opening paragraph of §8.3 on p. 88. The complete section is printed below:

8.3. *On received wisdom*

It is clear that little progress in cometary science can be expected without an *in situ* mission to a comet which remains in its vicinity as its atmosphere evolves, and directly samples its core material. Several comets would be even better. However, it is likely that such a project will turn out to be valuable for none of the reasons that we can imagine today. The way that a space mission can change one's scientific perspective has been admirably summarized in Wood (1987), and one can do hardly better than to finish with a quotation from that paper:

> "Paper experience has shown that stepping up from remote observations to detailed laboratory studies on Earth doesn't merely sharpen our perception of a system—it totally changes our outlook [...] A striking example of this change in scientific perspective can be cited: the revolution in our knowledge of Earth's moon that occurred when samples of it were brought to Earth in 1969–72. In spite of the proximity of Earth and Moon, the amount that had been learned about the latter by remote observations prior to 1969 was really very small. Scientists in the 1960s argued about the meaning of such observational minutiae as oddly shaped craters ('dimple craters') and the photometric function of the lunar surface (evidence for highly anomalous behaviour of lunar dust?); debated whether the lunar craters were produced by impact or volcanism and whether the maria were lava flows, dust deposits, or dry lake beds; and speculated about the composition of the lunar crust: granite, andesite, basalt, ultramafic rock, or chondritic meteorites? The return of samples swept all this away in an instant [...] Most of the scientists who were vocal about the Moon in the 1960s were not heard of after 1969."