the string is nearer to the source than the Earth. The string loops decay by the emission of gravitational radiation and finally radiate most of their energy in a complex mixture of coherent vacuum-phase waves and high-energy particles with energies up to 10^{15} GeV for grand-unification strings[33]. The particles with energy $E > 10^{10}$ GeV will be degraded by interactions with the microwave background for $z > 0.2$. It is a possibility that the highest-energy cosmic rays are the relics of cosmic strings that decayed in intergalactic space at values of $z < 0.2$. The cosmic ray spectrum should extend to energies beyond the limit of the current measurements[34] at $E \approx 10^{11}$ GeV to 10^{15} GeV.

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Infrared emission by organic grains in the coma of comet Halley

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Spacecraft[1] and ground-based[2–5] observations of comet Halley in the near-infrared reveal a triple-peaked emission feature near 3.4 μm, characteristic of C–H stretching in hydrocarbons (–CH_3 and –CH_2– alkanes). Here we discuss transmission spectra of organic residues produced by laboratory irradiation of candidate cometary ices, which serve as the basis for a model of emitting cometary dust. The laboratory synthesis of solid organic residue from irradiated low-occupancy methane ice clathrate simulates the radiation processing experienced by comet Halley. The transmission spectrum of this residue, convolved with a simple two-component thermal emission model based on the spacecraft-determined dust distribution in the Halley coma, fits the 3.4 μm feature, provides optical depths in excellent agreement with those observationally determined, and accounts for the absence of features at longer wavelengths (despite their presence in transmission spectra of typical ice irradiation residues).

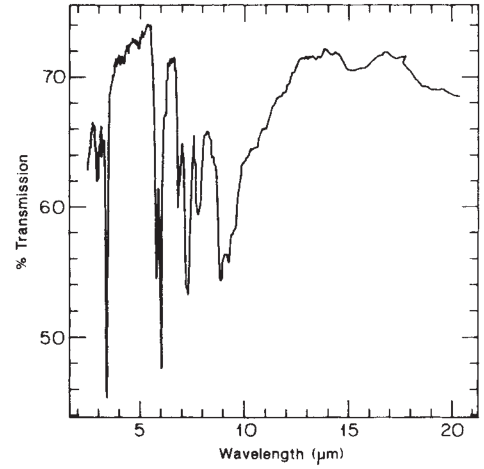

Fig. 1 Transmission spectrum of irradiated methane clathrate residue (after ref. 13).

The 3.4 μm feature has the broad, structureless character expected for a solid-phase origin, although the best resolution available[4], $\lambda/\Delta\lambda \sim 400$, is insufficient to rule out blending of a variety of lines from gas-phase molecules. If due to infrared fluorescence, a production rate for CH–X molecules in the gas phase ~0.2 that for H_2O seems sufficient to account for the observed flux in the 3.4 μm feature in ground-based spectra[4], in agreement with results from the Vega fly-by (M. Combes, T. Encrenaz & V. I. Moroz, personal communications). Some contribution to the 3.4 μm feature by gaseous emission is therefore expected[6]. However, in this letter we demonstrate that a simple model based on thermal emission from small, hot, organic or organic-coated grains in the Halley coma can readily account for this feature. Such a model is given credence by the fact that Vega mass spectrometry shows that ~80% of the dust encountered in the Halley coma is richer in carbon and nitrogen than C1 carbonaceous chondrites[7]. Further analysis suggests that most particles consist of a predominantly chondritic core surrounded by a complex organic mantle[8]. Thus there is direct evidence for small organic grains in the coma, with typical particle size ~0.1 μm (ref. 9).

In cometary ices, clathrate hydrates are thermodynamically favoured[10], and the most probable unprocessed form of hydrocarbons is the methane clathrate. Proton[11] or γ-ray[12] irradiation of pure CH_4 ice produces an organic residue that shows a 3.4 μm absorption feature as does charged particle irradiation of CH_4 clathrate and other hydrocarbon/H_2O ices[13,14]. The transmission spectrum for one such irradiated ice residue, that of a low-occupancy (200:1) $H_2O:CH_4$ methane ice clathrate, is shown in Fig 1. (This feature is by no means present in all organic solids; it is absent in the solid irradiation products of simulated uranian and neptunian atmospheres[15].) As comet Halley approaches the Sun, icy grains are ejected from its surface or jetted from its interior, and the ice sublimes. The refractory organic residue, probably stable to temperatures of 500–1,000 K (ref. 16), remains largely in solid form (though some evaporation may contribute to gas phase fluorescence) and, heated by solar radiation, emits in the infrared. This process is well modelled in our laboratory experiments, where the ice is first irradiated, then completely evaporated by high-vacuum pumping at temperatures ~425 K before the transmission spectrum of the residue is determined[14].

A number of regimes can be distinguished for the irradiation of C-rich ices in comet Halley. We have systematically examined this irradiation history elsewhere[17]. In its present short period orbit, Halley experiences a flux of ~1 keV solar wind particles, with a typical penetration depth in ice ≲1 μm. During its ~4.5 Gyr residence in the Oort clud, the nucleus experienced a total cosmic ray dose $\sim 10^{21}$ keV cm^{-3} of ~1 GeV particles, with significant irradiation extending to depths of 10 m or more. Finally, during its first ~10^6-10^7 yr the entire nucleus was processed by decaying radionuclides (chiefly ^{26}Al) incorporated into the comet during its formation, perhaps responsible for a dose ~10^{20} keV cm^{-3} (ref. 18). Integration of the observed production rates of OH and dust suggests that comet Halley loses a depth ~5 m each orbit, so that most of the irradiation products due to solar wind and cosmic rays should be quickly lost to space. The observed low-albedo crust of the comet may be of primordial origin[19]. While some fraction of the emitting dust may be fragments of this crust, most is probably jetted from the interior, with organics thus due mainly to processing by radionuclides and pre-accretion irradiation.

Laboratory irradiation of CH_4 clathrate[14], and other C-containing ices[20,21] indicates a synthesis efficiency of 1-10 C or O atoms incorporated into involatile organic product per keV applied to the sample. The total yield of *all* products (including more volatile simple hydrocarbons through C_5 and probably CO), is higher by about an order of magnitude[14]. Were CH_4 present in saturated clathrate form ($CH_4 \cdot 5.75H_2O$), for an average cometary density ~1 g cm^{-3} there would be ~5×10^{21} C atoms cm^{-3}. This is almost certainly a considerable overestimate of the amount of CH_4 present[22]. Typically $[C]/[O] \geq 1$ for such organic products. Thus we have the conservative conclusion that the succession of radiation environments experienced by comet Halley before being perturbed into its present short-period orbit should result in an outer cosmic ray-processed layer 1-10 m thick, irradiated at ~10^{21} keV cm^{-3}, in which ~100% of all CH_4 has been converted to (volatile and involatile) organic products, overlying an interior uniformly processed by radionuclides at a dose ~10^{20} keV cm^{-3}, in which ~10% of the CH_4 inventory has been processed.

Figure 2 shows the spectrum of comet Halley observed by Wickramasinghe and Allen[2] on 31 March 1986 (heliocentric distance $R = 1.16$ AU, geocentric distance $\Delta = 0.549$ AU), and our best fit (see below) to their data. The overall shape of the spectrum is that of a continuum which is well-fit by the sum of scattered sunlight (known from observations made that night at shorter wavelengths) and a 350 ± 10 K black body. The emission feature at 3.4 μm is evident. In addition, there is an absorption feature between 3.0 and 3.1 μm, which is apparent in other ground-based[3] and spacecraft[1] observations; it has been tentatively identified as due to H_2O ice[1]. We have not incorporated such absorption into our model.

At a heliocentric distance $R = 1.16$ AU, a black body would be expected to have a temperature ~280 K. The fact that the shape of the continuum is best fit for 350 ± 10 K indicates the presence of small (submicrometre) grains which, being inefficient emitters in the infrared, heat to temperatures well above black body equilibrium. In reality, of course, no single temperature can be ascribed to the dust responsible for the continuum emission: the observed flux is an integral over emission from grains of all sizes, each at different temperatures. In the optically thin case (an assumption justified below), we have

$$F_\lambda = \Omega \int \tau(\lambda, a) B_\lambda[T(a)]\, \mathrm{d}a \qquad (1)$$

where $B_\lambda[T(a)]$ is the Planck function per μm wavelength per particle radius a, Ω is the solid angle subtended by the telescope at the source, and the wavelength- and radius-dependent optical depth $\tau(\lambda, a)$ is given by

$$\tau(\lambda, a) = \int n(a) \pi a^2 Q(a)\, \mathrm{d}l \qquad (2)$$

Here $n(a)$ is the number density, πa^2 is the geometrical cross section, and $Q(a)$ is the extinction efficiency factor for a particle of radius a. The integral is taken along the line of sight through the source.

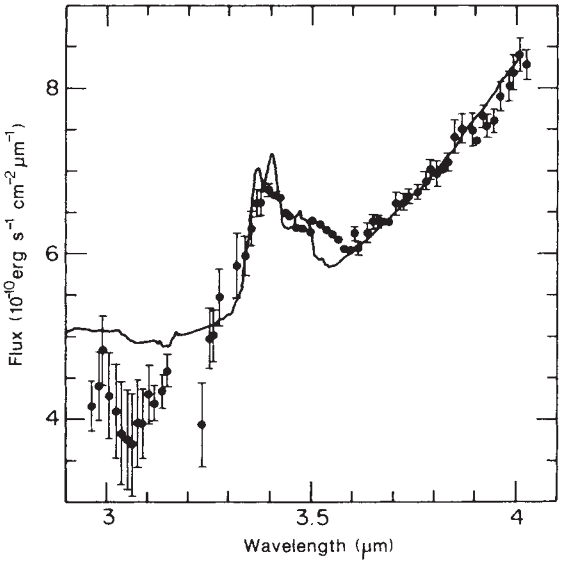

Fig. 2 Best fit (solid curve) to 3-4 μm spectrum of comet Halley (ref. 2). The absorption feature at ~3.1 μm, probably O-H stretch, is not modelled.

Modelling dust emission from an actual comet is a matter of making sufficient approximations to allow equations (1) and (2) to be computed. $Q(a)$ is not only a function of particle radius, but of chemical composition and frequency as well; $T(a)$ depends on the absorptivity of the grain near the peak of the solar spectrum; and $n(a)$ is in general unknown.

Hanner[23] has fit cometary continuum emission with a two-parameter model for $n(a)$, calculating $T(a)$ via Mie theory. For $\lambda \gg a$, $Q(a) \propto 2\pi a/\lambda$, with the proportionality factor composition-dependent[24]. The Giotto spacecraft measured the mass spectrum of dust along its trajectory through the Halley coma[25]. Using the Divine *et al.*[26] pre-encounter model of the density-radius relationship, this mass spectrum yields either the geometrical filling factor (cross section per unit area) or number density of dust along the Giotto trajectory as a function of particle radius[25]. Unfortunately, we cannot hope to use the resulting distribution in more than a crude way to model infrared emission from comet Halley, due to its extreme time-variability. Most comets exhibit a $1/R^4$ brightness dependence in heliocentric distance R, indicating a $1/R^2$ dependence for dust production. This general trend is observed for comet Halley as well, although the comet varies by as much as a factor of 7 from this trend over several days[27]. Indeed, over a period of just 3 nights' observations, Wickramasinghe and Allen found a 4-fold variation in overall flux, and an uncorrelated variation of a factor of 4.5 in the emission feature. Similarly, 5-13 μm observations show that the 10 μm silicate dust feature varies by as much as a factor of 2 relative to the continuum[28]. Thus the composition and/or $n(a)$ of the emitting dust is highly time-variable. There are two weeks between the Giotto and Vega fly-bys and the Wickramasinghe and Allen observations. To evaluate equations (1) and (2) for the ground-based spectra therefore requires the introduction of free parameters to describe the dust distribution, or else a much simpler model. In this letter, we use a simple two-component model to explain the spectrum shown in Fig. 2.

The simplest model for dust emission from the Halley nucleus—constant velocity outflow for particles of a given radius—predicts that dust number density $n(a, r)$ should vary as $1/r^2$, where r is the nuclear distance. This model is roughly confirmed by spacecraft observations[25]. The trajectory of the Giotto spacecraft defines a chord through the Halley coma, with closest approach to the nucleus $r_G = 600$ km. With the $1/r^2$ relation, the geometrical filling factor $A_G(a)$ integrated along the Giotto trajectory for particles of radius a can be determined:

$$A_G(a) = 2\int_{r_G}^{R_c} n(a, r)\pi a^2\,dr \approx 2n(a, r_G)r_G\pi a^2 \qquad (3)$$

where $R_c \equiv 5\times10^4$ km is the radius of the coma. Combining the Divine *et al.*[26] density-radius model for the Halley dust with the empirical formula for dust fluence as a function of mass experienced by Giotto[25], we find the total filling factor summed over all particles to be $A_G = 8.3\times10^{-4}$.

Individual dust grains with $a \gg \lambda$ are optically thick at wavelength λ, and thus contribute an optical depth to emission at that wavelength (at which they emit as black bodies) appropriate for their geometrical cross section. Taking particles with $a \gtrsim 10$ μm to be optically thick at the wavelengths of interest here, we find such particles comprise ~77% of the geometric cross section in the Halley coma.

Wickramasinghe and Allen observed using a rectangular aperture measuring 10×5 arc seconds, centred on the position of greatest infrared flux. Taking this as the nucleus, we can integrate A_G, correcting for its variation with $1/r^2$, to find the total geometric cross section, A_{tot} of all dust in their field of view. We find $A_{tot} \propto$ aperture size; that is, we recover the usual result that observed thermal flux is proportional to aperture size[27]. Incorporating the $1/R^2$ dependence of dust production on heliocentric distance (for 14 March 1986, the day of the Giotto fly-by, $\Delta = 0.96$ AU and $R = 0.90$ AU), integration gives $A_{tot} = 1.4\times10^3$ km^2, which is the total geometric emitting area of the dust in the Wickramasinghe and Allen aperture. With a radius ~5 km, the nucleus contributes ~80 km^2, or about 5% of the total emitting area. Thus the observed continuum radiation is due almost entirely to the dust in the coma. Yet this dust is optically thin: dividing A_{tot} by $\Omega\Delta^2$, we find a geometrical filling factor $A_{WA} = 1.9\times10^{-4}$.

The simplest approximation to equation (1) for the continuum radiation is to treat $\tau(\lambda, a) = A_{WA}$, and the Planck function to be that appropriate for $T = 350$ K. Such an approximation crudely averages together the effects of the small, hot particles with the larger, optically thick particles at 280 K. This approximation mitigates the need to 'fine tune' several parameters, and we will demonstrate that it works extremely well.

In our model, the emission feature at 3.4μm is due to small, hot, optically thin organic or organic-coated grains. The transmission spectrum of the organic residue of irradiated CH$_4$ clathrate allows us to model the wavelength-dependent optical depth of such grains directly. We have $\tau_\lambda = N_1\sigma_\lambda$, where N_1 is the column density of the residue in the coma and $\sigma_\lambda = N_2^{-1}\ln(t_\lambda^{-1})$ is the wavelength-dependent cross section derived from the laboratory-measured transmission. Here N_2 is the column density through the residue sample in the laboratory, and t_λ is the transmissivity of the sample (given by Fig. 1, with maximum transmissivity set equal to 1).

Using the optical constants[29] for an organic residue formed by sparking 10% CH$_4$ in a nitrogen atmosphere, both Hanner[30] and Lamy and Perrin[31] have found that 0.1 μm grains will reach temperatures ~500 K at ~1 AU; 0.1 μm grains composed of magnetite or glassy carbon will have somewhat higher temperatures (~600 K) at this heliocentric distance[23]. As the optical constants of irradiated ice residues are at present unknown, we adopt ~500 K as a temperature for the emitting organic grains. We therefore derive the following expression for the 3-4 μm flux measured by Wickramasinghe and Allen: $F_\lambda = C_\lambda + \Omega\tau'_\lambda B_\lambda(T = 500\text{ K}) + \Omega\tau B_\lambda(T = 350\text{ K})$, where C_λ is the scattered solar flux and $\tau'_\lambda = \beta(a/\lambda)\ln(t_\lambda^{-1})$. Here β and τ are parameters varied to provide a best χ^2 fit to the data. In practice τ is tightly constrained by the Giotto-determined filling factor in the Halley coma, and an upper bound is placed on τ'_λ (hence β) by the filling factor represented by the optically thin grains.

Our best fit is shown in Fig. 2; χ^2-minimization yields the values $\tau = 1.4\times10^{-4}$, and $\beta = 1.1\times10^{-5}$ (giving $\tau'_\lambda = 1.1\times10^{-7}$ at $\lambda = 3.4$ μm). τ compares very well with the value predicted by a simple geometric filling factor model: τ is within 25% of the value A_{WA} found by integrating the Giotto-determined dust distribution (adjusted for heliocentric distance) over the aperture used by Wickramasinghe and Allen. This agreement is much closer than the highly variable nature of Halley dust emission allows us to expect.

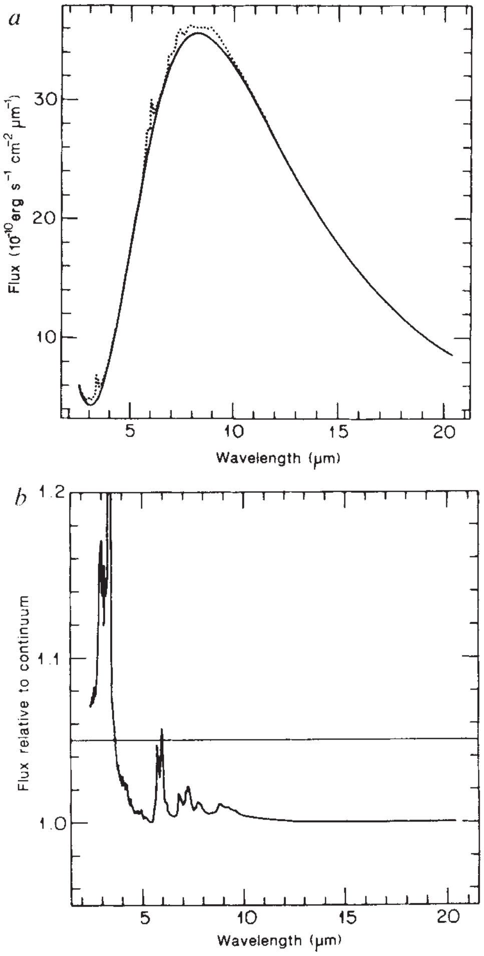

Fig. 3 *a*, The comet Halley 2-20 μm spectrum predicted by our model (taking $T \sim 500$ K for the small organic emitters), compared to that of a 350 K blackbody. *b*, The predicted 2-20 μm spectrum, after dividing out the continuum. Only the 3.4 μm feature is resolvable above the 6%-above-continuum level (indicated by the solid line).

The optical depth found for the small organic grains $\tau'_\lambda = 8.0\times10^{-4}\tau$, lying well within the upper bounds placed by the Giotto-determined dust distribution. Combining the Divine *et al.*[26] density-radius relationship with the Giotto mass spectrum[25], we find that dust particles with a ≤ 0.1 μm contribute a filling factor $\sim 1.0\times10^{-3}\,A_G$; particles ≤ 1.0 μm contribute $\sim 2.2\times10^{-2}\,A_G$, and particles ≤ 10 μm $\sim 0.23\,A_G$, where A_G is the total filling factor found by Giotto.

The triple-peaked emission feature predicted by the laboratory-measured transmission spectrum is seen to be slightly too narrow to match perfectly the observed Halley spectrum. The width of the laboratory feature is, however, somewhat influenced by radiation dose and temperature, dependencies which we intend to explore in future experimental work. Finally, we must address the question of other emission features predicted by our model. The transmission spectrum in Fig. 1 exhibits a variety of features at $\lambda > 3.4$ μm, not present in a set of 5-13-μm spectra of Halley's comet taken by Bregman *et al.*[28]. However, if the parameters determined above in modelling the 3-4 μm spectrum are used to model the Halley spectrum out to 20 μm (Fig. 3*a*), it is found that all higher-wavelength features evident in Fig. 1 are greatly suppressed relative to the continuum. The continuum optical depth $\tau \sim 10^3$ times the optical depth due to the emitting organics (τ'_λ), so that only near the minimum in the continuum radiation can an organic emission feature make a significant contribution. The 3.4-μm feature is the sole feature near that minimum, lying at the intersection of the scattered solar and 350 K black body curves.

In Fig. 3*b* we divide out the continuum to examine the strength of the individual emission features. Only the 3.4 μm feature rises over the level 10% above continuum, and the peaks at ~6 μm are too narrow to be detectable at the wavelength resolution ($\Delta\lambda/\lambda \sim 0.02$) of the Bregman *et al.*[28] observations above the ~5-6% over background level. Although these observations show no 6 μm feature to the 2% level (L. Allamandolla, personal communication), we consider the predictions of our model to be in sufficient agreement with this limit of detectability, as the optical depths appropriate for fitting the 3.4 μm feature for 31 March 1986 cannot be exactly appropriate for other dates (indeed, had we fitted Wickramasinghe and Allen's observations of 30 March, the predicted 6 μm feature would be resolvable only below ~3% above continuum). Among other uncertainties, the strength of the 6 μm feature relative to that at 3.4 μm is expected to vary with radiation dose; CH_4 clathrate is certainly not the only C or N-containing ice initially present in comet Halley; the temperature 500 K calculated from optical constants for a gas-phase N-rich product may not be correct for an ice residue [indeed, taking $T \sim 600$ K for the organic emitters (the temperature appropriate for glassy carbon grains) reduces the strength of the 6 μm feature by a factor of 2 (ref. 17)]; and most importantly, the simple two-component model used here is too crude to expect precise agreement with observation. Nevertheless, even this simple model demonstrates a physical mechanism for the suppression of higher-wavelength features relative to that at 3.4 μm.

As the comet moves away from perihelion, the intersection of the scattered solar spectrum and the comet's thermal emission spectrum will move to longer wavelengths. Thus, relative to the continuum, we expect the 3.4 μm feature to be suppressed and those at longer wavelengths progressively enhanced—as long as the comet retains a coma. Future comet rendezvous missions will be well placed to test this prediction of our model (which we present quantitatively elsewhere).

Finally, we note that the continuum temperature in the 5-13 μm range[28], adjusted for heliocentric distance, agrees to within the uncertainty with the 350 ± 10 K continuum temperature found by Wickramasinghe and Allen. That is, approximating continuum emission by a 350 K temperature averaged over all dust sizes remains valid through the wavelength region of interest. Herter *et al.*[32] have shown, however, that the continuum emission cannot be fit by a single black body temperature to 30 μm, where the more rapid fall-off of high-temperature emission by small grains evidently begins to render our approximation invalid.

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Note added in proof: Allen and Wickramasinghe[33] have now reported observations of a 3.4 μm emission band in comet Wilson, closely matching the comet Halley feature for approximately the same heliocentric distance. It is surprising that two comets with such evidently different histories should display such nearly identical infrared spectra: Apparently the characteristics of cometary organics are remarkably similar for both dynamically new and old comets strengthening the case made here for the primordial origin of these molecules.

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Atmospheric radioactivity and variations in the solar neutrino flux

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Measurements[1] of the flux of neutrinos emitted as by-products of hydrogen fusion reactions in the Sun's core bear on questions ranging from stellar evolution theories[2,3] to the question of the neutrino mass. Attention has been devoted recently to possible time variations in the neutrino flux data, and some investigators have found an inverse correlation with the 11-year sunspot cycle[4–7], although there is still some debate about the statistical significance of this correlation[8]. The neutrino luminosity of the Sun is not expected to vary on timescales less than one million years, so alternative sources of neutrinos have been invoked to explain the temporal variations. Galactic cosmic rays have been considered to be a likely candidate, as their intensity at the Earth's orbit varies inversely with the activity of the Sun. Here we present a calculation of the inventory of positron emitters in the Earth's atmosphere that results from hadronic cascades initiated by galactic cosmic rays, and the variation of this source of low-energy neutrinos with the 11-year solar cycle. Our results rule out the possibility that cosmogenic neutrino emitters are responsible for an apparent solar-cycle dependence in Davis's solar neutrino experiment[1]. As atmospheric secondary-particle decay was previously eliminated as a significant neutrino source[9], any such variations, if corroborated over the next sunspot cycle, would appear to be caused by phenomena outside the Earth's atmosphere, most likely in the Sun itself.