Detection of atomic oxygen trails of small comets in the vicinity of Earth

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Abstract. Transient trails of emissions at far–ultraviolet wavelengths have been detected by the Earth Camera on board the Polar spacecraft. These emissions are interpreted in terms of resonantly scattered solar radiation from atomic oxygen at 130.4 nm. The temporal durations of the emission trails are typically tens of seconds. The maximum brightnesses of the shorter trails are usually lesser than those of the longer trails which indicate that the shorter trails are farther from the spacecraft. The rate of occurrence of these trails is approximately 5 to 10 each day. These events are interpreted as the signatures of the disruption and rapid dissipation of small comets in the vicinity of Earth.

Observations

The Polar spacecraft was launched on 24 February 1996 into an eccentric orbit with perigee and apogee altitudes of 5170 km and 50,510 km, respectively, an orbital period of 17.6 hours, and an inclination of 86°. The apogee is positioned over the northern polar regions. The details of the design of the far–ultraviolet camera, i.e., the Earth Camera, which is part of the Visible Imaging System (VIS) are given by *Frank et al.* [1995]. This imager takes advantage of the spacecraft despun platform and stares at Earth with a field–of–view with dimensions 20° × 20°. An image intensifier which is serviced with a charge–coupled device (CCD) is used to obtain simultaneously accumulated responses in an array of 256 × 256 charge–collecting sites (pixels). An image obtained with this camera is shown in Figure 1. The wavelength window is 124 to 149 nm. The sunlit atmosphere is readily evident in this side view of our planet, and weak auroral emissions are to be seen as a dim northern crown at the top of the dayglow image. These emissions are primarily due to those from atomic oxygen (OI) in the upper atmosphere at 130.4 nm. The remarkable feature in Figure 1 is the unexpected light trail positioned at the right and above Earth's limb. This light trail is composed of more than two hundred pixels with responses that exceed the threshold of the sensor array. Close inspection of the light trail finds that there are at least two dark strips across the trail. This feature is important in complete elimination of the possibility that the trail is a spurious event due to the passage of an energetic charged particle through the sensor array. The brightness along the trail is presented in detail in Figure 2. This chart was constructed by finding the center of the trail in the pixel array of Figure 1, then summing the pixel responses for the six pixels centered on the trail in a given horizontal row, and plotting three–row boxcar averages as a function of row number. Row numbers increase from top to bottom of Figure 1.

There are several minima in the intensities of the trail as seen in Figure 2. The exposure time for the frame is 36 s. One frame is telemetered each 54 s. The minima labeled as A and B are due to electronic shuttering of the camera for two purposes. First the large antenna booms on the spinning section of the spacecraft can scatter light into the sensitive camera. The camera is mounted on a stabilized, nonspinning platform. This contamination of the images is avoided by electronically shuttering These decreases are labeled as A in Figure 2. The time interval between these minima is the spacecraft spin period, 6 s. In addition the imbalance of the spinning section of the spacecraft causes the nonspinning platform to move cyclically with the spin period of 6 s. This introduces a cyclic motion of the camera's field–of–view which degrades the angular resolution. This resolution is also restored by electronically shuttering the camera in synchronization with the spin. This shuttering causes the minima labeled B in Figure 2. The elapsed time between these two minima is thus 6 s. In summary, with respect to one of the intensity ansae due to spacecraft imbalance, there are two angular sectors for which the electronic shutter is open during each 6–s rotation of the spacecraft, 87.2° to 17.6° as the spacecraft rotates toward the ansa and 2.8° to 72.4° after the spacecraft rotation passes the ansa. The rest of the rotation finds the shutter closed during the two intervals, A and B. The corresponding pixel resolution for viewing a star is improved to 2.2 pixels relative to the 4.8 pixels without such compensation. For the following Figure 3 the above angular sectors are 70.3° to 17.6° and 2.8° to 70.3°, respectively, and the angular resolution is improved to 1.6 pixels. These shuttering sequences guarantee that an object is being imaged and that the trails are not instrument artifacts due to penetrating particles into the sensor. The latter events are removed from the images.

A second example of a trail is shown in Figure 3. Although the apparent angular speed is less by a factor of about two than that for the trail shown in Figure 2 the overall shape and duration of the light curve are similar for both events. Because the response decreases for the boom and despun blankings are closer together, a 3–row running average of the responses has not been performed. Examination of the light curves in Figures 2 and 3 finds that the blanking effects will disappear as the apparent angular speed of the object decreases. Although
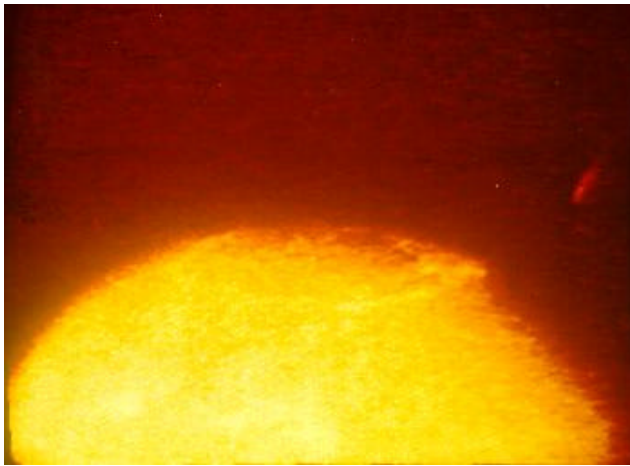
Figure 1. An image of sunlit Earth as seen at wavelengths in the far–ultraviolet at 1642 UT on 23 September 1996 as taken with a camera on an Earth–orbiting spacecraft. The image has a mottled appearance because intensities in this spectral window are factors of millions dimmer than those for visible wavelengths and thus show the statistical effects for photon counting. The spacecraft is positioned at an altitude of 25,850 km, and Earth's limb is seen on the left–hand side and the terminator on the right. The trail in the upper right–hand side of the image is the record of the final moments of the disintegration of a small comet.
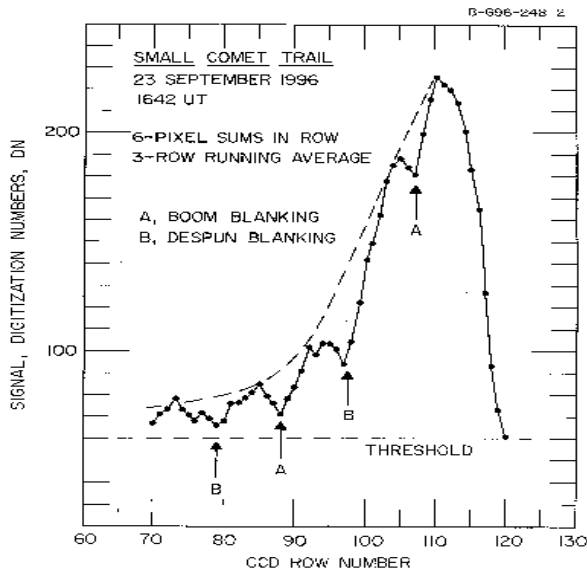

Figure 2. The intensities along the trail shown in Figure 1. The cloud of gases is moving relative to the line–of–sight, expanding in radius, and brightening. The image is the record of the presence of atomic oxygen in the gas cloud. The trail exhibits the stamp of validation with the periodic minima due to instrument blanking. This assures that the trail is not an instrumental effect. The position of the small comet is estimated at about 2400 km from the spacecraft at the time of disruption.
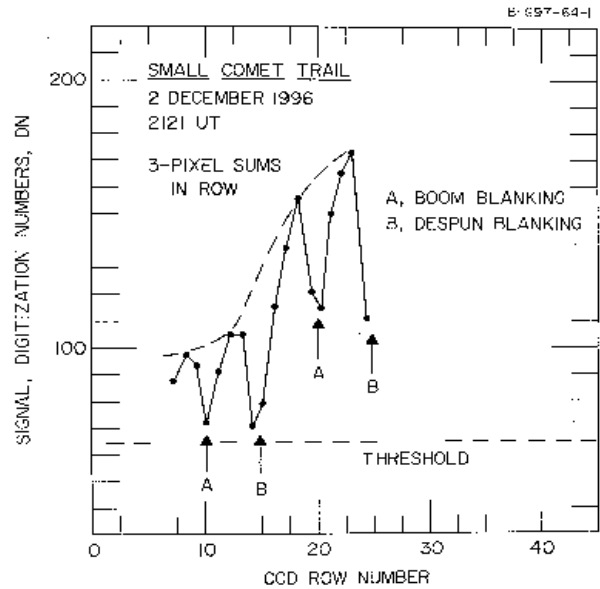

Figure 3. A second example of the light trail from the disruption of a small comet in the vicinity of Earth at 2121 UT on 2 December 1996.

Although light curves of this latter type are evident in the images they are not used because the time marks due to blanking are absent and thus elimination of possible energetic particle events is compromised. The example of the light curve in Figure 3 is also included for the purpose of demonstrating that these events occur over periods of at least months. In fact the frequency of these events is in the range of 5 to 10 each day. The shapes of the light curves, i.e., normalized intensity versus time, are very similar for all the events. The absolute intensities are generally lesser for the objects with lesser angular speeds. This feature suggests that the objects with lesser angular speeds are more distant from the spacecraft.
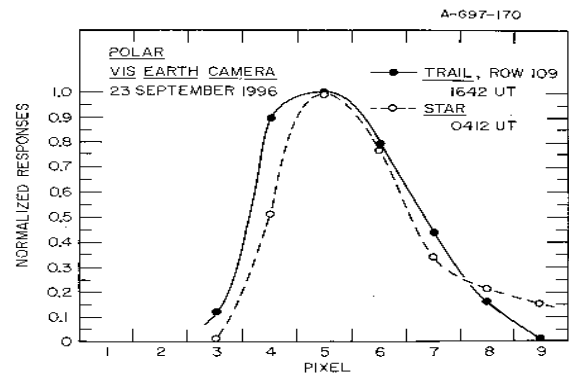

Figure 4. The normalized responses as a function of pixel number across the trail for the event shown in Figure 2 and for a star with similar maximum intensities.

The apparent angular widths of the trails are generally less than the angular resolution of the Earth Camera, function of pixel number across the trail about two pixels or 0.16°. However, the width of the trail at maximum intensities in Figure 2 begins to exceed this width. This is demonstrated by the normalized responses shown in Figure 4 for the trail and a star. There is no star in the field–of–view of Figure 1. The selected star is taken from the same orbit. The width of the trail is estimated as about 3 pixels or 0.24°. The apparent angular speed for the brighter trail presented here in Figures 1 and 2 is about 0.24°/s and that for the dimmer trail in Figure 3 is about 0.11°/s. With the assumption that the present objects are part of the small comet distribution which is observed at altitudes < 3000 km as atmospheric holes and as trails in the emissions from the radical OH then their apparent speeds are typically 10 km/s [*Frank and Sigwarth,* 1993; 1997a; 1997b]. Then the ranges of the two above trails from the spacecraft position are about 2400 and 5500 km, respectively. Regardless of any reasonable assumption of apparent speed the trails are located at altitudes in excess of 10,000 km above Earth's surface.

The above findings severely constrain the interpretation of the light curves. First of all the uniformity of the light curves eliminates the possibility of debris in the vicinity of the spacecraft. Secondly the emissions are detected for a brief period, about 15 to 20 s. We interpret these intensities as rising over a period of about 15 s and decaying within 2 or 3 s. Of course, the light curve can be interpreted as rising in 2 or 3 s and decaying in 15 s. In any case, the event is impulsive with time scales of tens of seconds.

Two plausible possibilities remain for the interpretation of these transient events, an exploding comet or an exploding dust ball. If the far–ultraviolet responses of the Earth Camera are due to reflectance of the solar radiation from dust then the brightness of the trail at visible wavelengths should be in the range of about 4,000 kiloRayleighs (kR) within the passbands of the Low–Resolution Visible Camera. For example, an upper limit of about 0.5 kR is found with the passband at 557.7 nm. Thus the trails are not due to dust. The possibility that the trails are due to broadband reflected sunlight from an expanding volume of snow from an exploding comet can be similarly eliminated.

Discussion

We have reported the remarkable discovery of transient trails of far–ultraviolet emissions with the Earth Camera on board the Polar spacecraft. The passband filter of the camera favors interpretation of the trails in terms of resonantly scattered radiation from atomic oxygen exposed to solar radiation. This wavelength is 130.4 nm. The time durations of these trails are typically tens of seconds. The brightnesses of the dimmer trails are usually less than those of the brighter trails which suggests that the dimmer trails are farther from the spacecraft. Apparent angular speeds of the objects responsible for the trails are in the range of 0.1 to 0.5°/s. The angular widths of the trails are less than the angular resolution of the Earth Camera, 0.16°, for the most part, with the occasional exception of the brighter trails with width about 0.24°. The brightness of these wider, resolved trails is about 5 kR. The observed occurrence frequency of the trails is about 5 to 10 each day. The above observed characteristics of the trails provide considerable constraints on models for their origins. To date we have found only two models which may satisfy the above constraints, i.e., the standard photodissociation of cometary water to produce the atomic oxygen and the direct release of atomic oxygen in the interior of the comet as suggested by recent observations of Ganymede. Even though the first model above fails to reproduce the time scale and intensities of the trail an overview of the computations with this model is useful for the reader.

Consider the expanding water vapor from the disruption of a small comet. The vaporization rate for bare snow is $\sim 1.7 \times 10^{18}$ H_2O molecules/cm²–s at 1 AU [*Delsemme,* 1982]. The cometary gases are not expected to be in dynamical equilibrium. If the comet mass is small enough then the process of vaporization can be transient with total vaporization in periods of tens of seconds. An estimate of the amount of water vapor N_w at time t after onset of disruption is $N_w = 1.7 \times 10^{18}$ $\pi(v_e t)^2$ $(t/3) = 1.8 \times 10^{18}$ $v_e^2 t^3$ molecules where v_e is the bulk expansion speed of the cometary material. The major line emission within the passband of the Earth Camera is that from resonant scattering of the solar flux by atomic oxygen at 130.4 nm, i.e., $O(^3P)$. The rate of increase of the number N_O of oxygen atoms at (^3P) from dissociation of the water vapor molecules at time t is $dN_O/dt = N_w f/\tau_d$ where τ_d is the photodissociation lifetime for water $= 8.2 \times 10^4$ s. The channel fraction f for $O(^3P)$ is 0.065 [*Combi,* 1996] and includes 0.034 for collisional relaxation of $O(^1D)$. The total number at time t then becomes $N_O = 3.6 \times 10^{11}$ $v_e^2 t^4$. The total rate of 130.4–nm emission at time t is $S_f = N_O g$ where g is the g–factor $= 6 \times 10^{-6}$/s. Then $S_f = 2.1 \times 10^6$ $v_e^2 t^4$ photons/s where v_e is in units of cm/s.

The observed photon source can be estimated from the light curve in Figure 2. Because the light curve does not fall to values near the threshold during blanking, the core of cometary material may have an extended tail. The responses of the Earth Camera due to the brighter core are estimated to be about 40 DN/s. The corresponding photon flux is $\sim 8 \times 10^3$ photons/cm²–s at the spacecraft. The source function $S_0 = 10^5 R^2$ where R is the distance from the spacecraft to source in cm. With $S_0 = S_f$ then $R^2 = 21$ $v_e^2 t^4$. For a reasonable expansion speed v_e in the range of 10^5 cm/s [*Feldman,* 1982] and an event time duration of 20 s, R = 1830 km and the total mass of the water vapor is $\sim 4 \times 10^9$ gm. The computed

diameter of the gas cloud is 40 km. For the observed angular diameter of ~0.24° at the peak of the emissions the corresponding diameter is ~8 km and is inconsistent with the above model diameter of 40 km. This extremely rudimentary model for the spatial distribution of cometary material assumes a homogeneous mixture of H_2O vapor and OI. For a tail length of ~100 km the optical depth for absorption of the 130.4–nm emissions by the water vapor is in the range of 10. A similar problem exists for the absorption of the solar far–ultraviolet emissions which photodissociate the water. The absorption cross–sections for both processes are similar, ~4–5 $\times$ 10^{-18} cm^2, and yield similar optical depths. Thus the observed magnitudes of the OI emissions cannot be achieved with this model. Another formidable inconsistency is the brief durations of the light trails, tens of seconds, and the relatively long photodissociation lifetime for water molecules, ~82,000 seconds.

On the other hand, recent observations of the hydrogen plasmas and hydrogen exosphere of Jupiter's moon Ganymede [*Frank et al.,* 1997; *Barth et al.,* 1997], the remote observations of its surface [*Spencer et al.,* 1995; *Calvin et al.,* 1996; *Noll et al.,* 1996], and laboratory measurements of the effects of Lyman–α and ion bombardment of water ice [*Westley et al.,* 1995; *Bar-Nun et al.,* 1985] provide ample evidence that particle and photon sputtering can result in the loss of hydrogen and storage of O_2 and O_3, also the radicals HO_2 and H_2O_2, in the icy Ganymede surface. There is no reason to believe that the exposure of the small comets to ultraviolet radiation and energetic charged particles over billions of years cannot yield the same excess of oxygen atoms and molecules. An overview of laboratory measurements of the effects of photon and charged–particle bombardment on icy bodies is recently given by *Johnson and Quickenden* [1997], and the possibility of microatmospheres of O_2 and O_3 in the icy surfaces is proposed by *Johnson and Jesser* [1997]. Simple considerations of energy deposition find that most of the OI should be positioned in the outer shells of the small comet. The OI would be then expected to be located in the optically thin, outer layers of the rapidly expanding gas cloud after disruption of the small comet. With this in mind let us revisit Figure 2. The total photon emission at the source at a range of 2400 km from the spacecraft (see previous Observations section) is $S_O = 10^5 R^2 = 5.8 \times 10^{21}$ photons/s at maximum intensities. Then the number of oxygen atoms required to produce the source strength at the maximum intensities is $N_O = S_O/g$) 9.5×10^{26} oxygen atoms. This corresponds to a mass of pure oxygen atoms of 2.5×10^4 grams. From previous observations of the phenomenon known as atmospheric holes it is known that the motion of the small comets, and hence the trail, should move in prograde motion and thus from left to right in Figure 2 [*Frank and Sigwarth,* 1993; 1997a]. The trail then

becomes the record of the release of atomic oxygen as the cometary water snow vaporizes with the maximum brightness occurring near the end of the vaporization process. The released atomic oxygen is very reactive and will rapidly combine with such atoms as carbon and nitrogen in the cometary gases. In fact the rapid decline in intensities at the end of the trail provides an upper limit for the time scale for the reaction times for atomic oxygen, about several seconds. This rapid removal of the atomic oxygen also explains why the trail is narrow and why there will not be a large–scale diffuse glow of 130.4–nm emissions across the sky. The upper limit on its angular width is about 0.24°, or about 10 km at the range of 2400 km as estimated in the previous Observations section. This interpretation of the trails of atomic oxygen emissions in terms of direct release accommodates their observed characteristics in a straightforward and economical manner (see beginning of this section).

If the lifetime of the atomic oxygen is only several seconds then the above estimate of the total amount of atomic oxygen which is released for a trail duration of 20 seconds will be increased by a factor estimated at about 4. This mass of atomic oxygen in the small comet is then 10^5 grams. Of course, in order to estimate the entire mass of a small comet it is necessary to know what fraction the atomic oxygen represents. This is currently unknown but reasonable estimates may be 10^{-2} or 10^{-3} which result in a total cometary mass estimate of 10^7 or 10^8 grams and in the range of water masses required to account for atmospheric holes [*Frank and Sigwarth,* 1993, 1997a]. However, the reader is advised that a more accurate account of the reactions which can yield the atomic oxygen from constituents such as O_2, O_3, C, OH, and others is likely to be necessary for the eventual understanding of the observed lifetime of the OI 130.4–nm emissions. Such a model for the kinetic and chemical processes during the comet's disruption is beyond the scope of this paper.

The occurrence rate of these trails of atomic oxygen emission at high altitudes above Earth's surface is much less than that required to account for atmospheric holes [*Frank and Sigwarth,* 1993; 1997a]. On the other hand, the Low–Resolution Visible Camera has been used to independently discover the trails of emissions of the OH radical at 308.5 nm at low altitudes, < 3000 km [*Frank and Sigwarth,* 1997b]. These OH emissions are accepted as the standard proxy for water in large comets. The occurrence frequency of the OH trails is similar to that for the atmospheric holes [*Frank and Sigwarth,* 1997a]. The most likely mechanism for small comet disruption are electrostatic forces which increase rapidly with decreasing altitude [*Frank and Sigwarth,* 1993].

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