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REPLY TO CRAGIN ET AL.

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Cragin et al. (1987) conclude that the decreases of ultraviolet dayglow intensities, or 'atmospheric holes', as reported by Frank et al. (1986a) are not geophysical events on the basis of their analyses of the telemetered count rates from the imaging instrumentation. Our examination of the analyses and results reported by Cragin et al. (1987) reveals serious errors and insufficiencies that eliminate the foundations for their claims. We provide here the proper theoretical treatment for anticipated instrument responses to small, opaque objects and the correct processing of the telemetered pixels. We find that our analyses further support our previous conclusion that the atmospheric holes are a geophysical effect.

We begin with the expected responses of the imaging photometer to the small, opaque objects as viewed against a statistically varying screen, i.e., the responses of the instrument to the unobstructed ultraviolet dayglow. Our treatment is extended to luminous and absorbing objects.

The response function for a single pixel is that due to rotation of the instantaneous field-of-view of the photometer during the sampling period (Frank et al., 1981). The instantaneous field-of-view intercepts a circular area of dayglow that is detected with more-or-less constant efficiency over this area. For our present work the angular diameter of the field-of-view is taken to be 0.29° for a step-function angular response of the instrument. The rotation of the field-of-view is 0.20° during a single sampling period and the next sample, i.e., the adjacent pixel, is initiated after 0.03° of rotation following termination of the previous sample period. The adjacent pixels overlap. With the above information the calculation of the pixel response function $f(x,y)$ is straightforward. We normalize $f(x,y)$, i.e., $\iint f(x,y)dxdy = 1$.

Consider an object within the field-of-view corresponding to a single pixel. The object is positioned at x_1, y_1 and is characterized by an absorption function $q(x,y;x_1,y_1)$. Then the mean fractional count for the pixel, $F(x_1,y_1)$, is

$$F(x_1,y_1) = \iint(1 - q(x,y;x_1,y_1))f(x,y)dxdy. \quad (1)$$

If the counting rate for the pixel is R_p in the absence of the intruding object, then with the object in the field-of-view the statistical distribution of counts R_b is binomial, i.e., $P(R_b|R_p) = n!p^v(1 - p)^{n-v}/v!(n - v)!$ where $p = F(x_1,y_1)$, $v = R_b$ and $n = R_p$. Thus the distribution of counts R_b due to the occluding object q at x_1, y_1 for an unobstructed screen count of R_p is determined. But the unobstructed screen response also statistically fluctuates about an average response $\bar{R}_p$, i.e., the distribution of R_p is Poisson and the above procedure must be repeated for each value of R_p and properly weighted with the Poisson distribution. At this point of the calculation, the responses R_b can be expressed in terms of standard deviations $S(x_1,y_1)$ from the average response, i.e., $S = (R_b - \bar{R}_p)/\sigma$, where $\sigma = (\bar{R}_p)^{1/2}$ is one standard deviation.

Because the objects are randomly distributed with respect to the pixel, the fluctuations S must be computed for all positions for which the object and the pixel overlap. This final calculation is accomplished by placing the object at positions on a dense equispaced grid x_1, y_1. The decrease of responses for adjacent pixels is found by evaluating equation (1) for the adjacent pixels at each position, e.g., $F_a(x_1, y_1)$. Because the pixel samples are independent, the average response for adjacent pixels is simply $F_a(x_1,y_1)\bar{R}_p$. For luminous features, the integrand of equation (1) becomes $q(x,y;x_1,y_1)f(x,y)$ and the luminosity provides a Poisson distribution of counts with average count $F(x_1,y_1)\bar{R}_p$ to be added to the screen count R_p. These sums become R_b in the calculation of $S(x_1,y_1)$. Thus for this case the object is considered as optically thin. For an object with both absorbing and luminous features the same procedures apply, i.e., the count distributions due to the absorption are evaluated for each value in the distribution of responses from the luminous region. The numerical computations for this latter case are thus straightforward, but more time-consuming. The reader may find computationally tedious the above rigorous treatment of the instrument responses to a small, absorbing and luminous object as seen against a statistically fluctuating screen. However our purpose demands such treatment and the results yield a certain simple elegance when compared to the observational results.

Cragin et al. (1987) provide an insufficiently rigorous treatment for even the less general case of a small, opaque object as seen against a statistically fluctuating screen.

Our calculations of the distortion of a Poisson distribution of pixel counts due to the presence of opaque, circular objects of various angular diameters are summarized in Figure 1. The occurrence frequency is given for bins of 0.2σ for all of our present graphs, the value used in the original paper of Frank et al. (1986a). All distributions are normalized to unity. The average value for the unobstructed pixel count is 50. The average decreases D for both pixels adjacent to all atmospheric-hole pixels with decreases $\leq -4.3\sigma$ are also shown in Figure 1. Thus if the angular diameter of the object is 0.30°, then both pixels adjacent to the hole pixel should exhibit an 18% decrease of responses on the average. The expectations are now sufficiently developed for comparison with observations.

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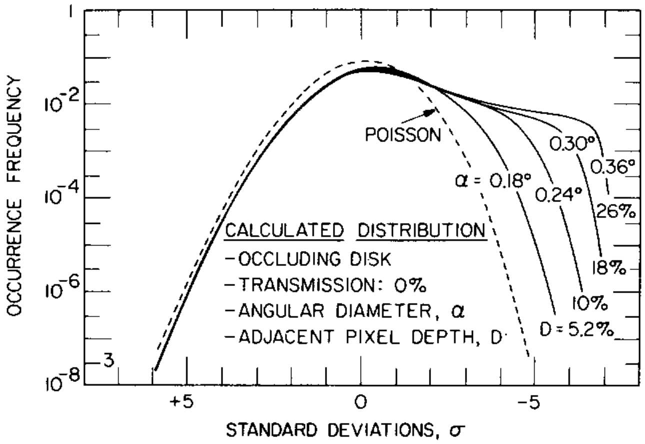

Figure 1. Calculated occurrence frequencies of pixel counts for opaque disks with the specified angular diameters.

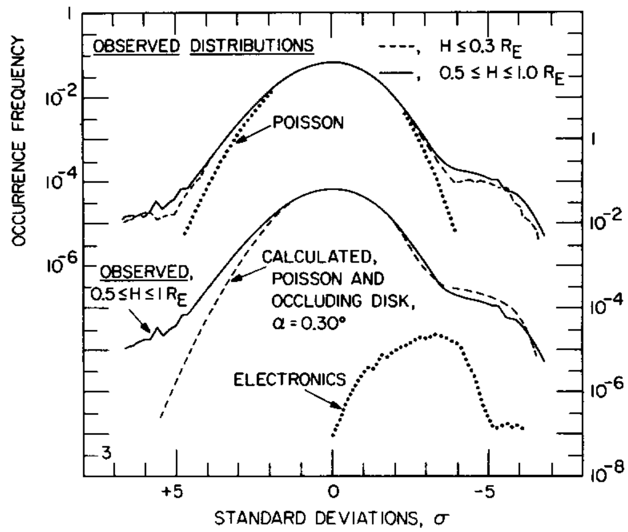

Figure 2. Observed occurrence frequencies of pixel counts for two altitude ranges (upper curves). Comparison of occurrence frequencies of pixel counts as observed at altitudes 0.5 to 1 R_E and as calculated for opaque disks with angular diameter α = 0.30° (lower curves).

Our originally published study of the statistical distribution of pixel counts (cf. Figure 1 of Frank et al., 1986a) utilizes a set of images for the period September 23 through October 6, 1981. Approximately one half of this image set is used by Cragin et al. (1987) in their analysis. In order to increase the number of pixels for low altitudes our present study includes images for the period September 23 through November 30, 1981 unless otherwise noted. For each selected orbit the same number of pixels is obtained for four altitude bins in order to prevent aliasing due to the temporal variations of atmospheric holes (cf. Frank et al., 1987). The four altitude ranges selected for binning the pixels are $H < 0.3\ R_E$ (R_E, Earth radius), $0.5 - 1.0\ R_E$, $1.5 - 2.1\ R_E$, and $3.0 - 3.3\ R_E$. The number of pixels in each bin is $\sim 9 \times 10^5$, with the exception of the lowest-altitude bin with $\sim 7 \times 10^5$ pixels. The distributions of pixels as a function of standard deviations from the average count rates (cf. Frank et al., 1986a) are shown in Figure 2 for the two bins at lower altitudes. All distributions are normalized to unity. Two characteristics of these distributions are evident: (1) the atmospheric holes (at $\lesssim -3\sigma$) are accompanied by bright features (at $\gtrsim +3\sigma$) and (2) the occurrence frequencies of both the atmospheric holes and the bright features are a factor ~ 2 greater for the higher altitude bin. This latter correlation establishes a relationship between the atmospheric holes and the luminous features.

Cragin et al. (1987) do not identify either (1) the altitude dependence or (2) the luminous features that are shown in our above results.

We may use now our interpretational tools and observational results to investigate the gross properties of the atmospheric holes. First an attempt is made to fit the observed deviations of the responses from a Poisson distribution to the expectations for opaque, circular objects. Our best fit for these opaque objects is shown in Figure 2. Observations in the altitude range 0.5 to 1.0 R_E are used. A Poisson distribution of unoccluded pixels is added to the distribution calculated for an object diameter of 0.30° (cf. Figure 1). The calculated distribution of responses and the observations for $\lesssim -3\sigma$ are in good agreement. This result indicates that at least part of the object may be similar to a small, opaque disk. However, the calculated result significantly departs from the observations in that the luminous features observed at $\gtrsim +3\sigma$ are unaccounted for.

Cragin et al. (1987) do not determine that the distribution of pixels for atmospheric holes as a function of deviation from the average count rates is similar to that expected for small, opaque objects (cf. our Figures 1 and 2).

We also include the results of a quantitative evaluation of the contribution of the counting electronics to the distribution of pixels in Figure 2. These false atmospheric holes are due to incorrect sampling of the count rate for a pixel if a pulse is being fed into the counter within ~ 0.5 μsec of the termination of the count interval. This characteristic is typical of counters that sample asynchronous signals and is given in the manufacturer's specification. The incorrect sampling can result in a reduced count rate, and thus a false atmospheric hole. Two parallel counters each are employed in the engineering model and the flight unit to sample every other pixel. Our engineering model of the electronics is used to evaluate the probability and values of the false readings as a function of photometer count rates. The contribution of the electronics to the distribution of pixels is determined by using the known properties of the counters as noted above and computing the distribution of false holes from the telemetered histogram of pixel count rates. This result is shown in Figure 2. Both the shape of the distribution and the magnitude of the occurrence frequencies are inadequate to account for the absorbing features at $\lesssim -3\sigma$ or the luminous features at $\gtrsim +3\sigma$. Thus we conclude that the atmospheric holes are not due to malfunction of the two parallel counters that are employed to sample the photometer responses for the flight instrumentation.

Cragin et al. (1987) do not identify any electronic malfunction that can yield the observed atmospheric holes.

The decreases of responses in adjacent pixels are determined by a simple binning of responses with respect to the event, or hole pixel, for a scan line of the image. A string of nine consecutive pixel responses is used, i.e., P_1, P_2, ..., P_9. Pixel 5 is a hole pixel if its response is $n\sigma$ less than the averaged responses of the four outer pixels, where σ is the standard deviation for this average. Then the response decreases in adjacent pixels 4 and 6 are simply $((P_4 + P_6) - (P_3 + P_7))/(P_3 + P_7)$. This result is not aliased by the conditional probabilities arising from selection of the hole pixel because the above four pixels are not used to select the hole pixel. In addition, this method effectively removes the effects of response gradients across the pixel string. In order to eliminate any effects of the occasional electronics-derived holes as discussed above, all pixels with default responses, e.g., 0, 1, 2 and 8, are removed. Adequate statistics are acquired by including all atmospheric holes observed from altitudes $\geq 3.1\ R_E$ for the period September 23 through November 30, 1981. The results are given in Table I. Averaged decreases in the responses of pixels adjacent to the atmospheric holes with depths $\leq -4.3\sigma$ are -1.4%. For comparison, the averaged decreases in adjacent pixels, with inclusion of the above default pixels, is -1.2% with a statistical uncertainty ±0.3% for hole depths $\leq -4.3\sigma$. The statistical uncertainty is derived from the quadratic sum of the standard deviations for the two summed bins $(P_4 + P_6)$ and $(P_3 + P_7)$. As expected, for holes with depths $\leq -3.5\sigma$ the response decreases shown in Table I diminish in amplitude as the contributions from the Poisson distribution and the objects with small angular diameters become important (cf. Figures 1 and 2).

TABLE I. Intensity Decreases in Adjacent Pixels

Atmospheric Hole Depth	Number of Holes	Adjacent Pixel Decreases	Statistical Uncertainty
$< -5.8\sigma$	179	-2.0%	1.0%
$< -5.6\sigma$	271	-1.4%	0.8%
$< -5.0\sigma$	776	-1.5%	0.5%
$< -4.3\sigma$	1,647	-1.4%	0.4%
$< -3.5\sigma$	3,581	-0.4%	0.2%

Cragin et al. (1987) report no evidence of these decreases in responses for adjacent pixels. Perhaps the unjustified use of filters for selection of events by Cragin et al. (1987) is one reason for their failure to find these decreases.

We now discuss the interesting task of determining the coarse distributions of opacities and luminosities that fit the observed distribution of pixel responses. The luminous feature is known to us for several years with the examination of thousands of atmospheric holes, i.e., a frequent bright feature adjacent to the atmospheric hole. These bright pixels are the source of the luminous features observed at $\gtrsim +3\sigma$. We first considered an opaque disk surrounded by a bright annular limb. Such an object is not found to provide the observed pixel distributions and the count decreases in the adjacent pixels. A physically reasonable alternative is an opaque disk with a bright, half-annulus as shown in Figure 3. This simple model is consistent with our proposal (Frank et al., 1986b) that the atmospheric holes are due to cometary water clouds at low altitudes and with motion roughly parallel to the ecliptic plane. The luminosity can be due to the impact of exospheric neutral gas and of ionospheric ions onto the cometary gases facing the direction of motion. For exospheric and ionospheric densities of $\sim 10^4/cm^3$, the energy flux is $\sim 1\ erg/cm^2$-sec. Because each scan line telemetered from the imaging instrumentation is taken in a fan of directions approximately perpendicular to the ecliptic plane, the luminous feature is oriented preferentially with respect to adjacent pixels. This orientation is shown in Figure 3 if the scan line is taken in the vertical direction. Although it is likely that a distribution of object sizes is being viewed, the single, simple object chosen provides a good fit to the observed pixel distribution as shown in Figure 3. The object is an opaque disk with angular diameter 0.33° with a half-annular bright limb with thickness 0.18°. The brightness of the limb is 180% of the ultraviolet dayglow, i.e., the luminosity due to the cometary gas alone is 80% of the dayglow intensities. The observed and computed decreases in the responses for adjacent pixels are also in good agreement, -1.4% (observed) and -2.3% (calculated) for count decreases of $\leq -4.3\sigma$ in the event, or hole pixel. For comparison this decrease for the opaque object only is 22%. Thus we find that the observed distributions of pixels previously identified with atmospheric holes are consistent with the distributions of such pixels expected from small, opaque objects within the field-of-view of the imaging instrumentation. Further our analysis is sufficiently extended here that the coarse determination of an associated luminous feature is possible.

Cragin et al. (1987) do not consider the above geometry for the cometary water clouds.

For altitudes near spacecraft apogee, the apparent angular motion of the atmospheric holes can be nearly equal to that for the scan lines. In this case the object can be detected in adjacent scan lines (cf. Frank et al., 1986c). The

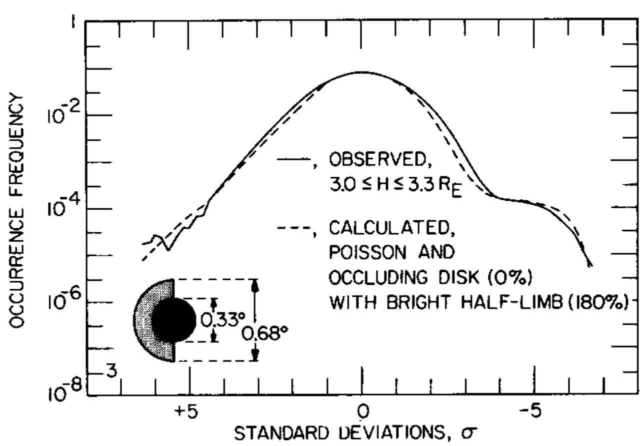

Figure 3. Occurrence frequencies of pixel counts as observed at altitudes 3.0 to 3.3 R_E and as calculated for opaque disks with bright half-limbs of the specified angular dimensions.

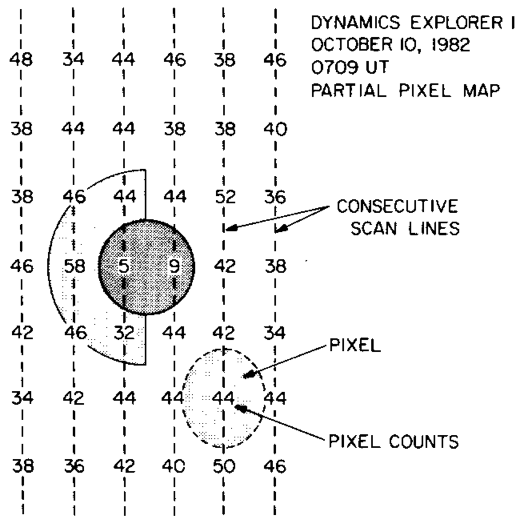

Figure 4. Pixel responses for a large atmospheric hole. Scan lines advance from right to left.

pixel responses, in counts, for such a sighting of an atmospheric hole are shown in Figure 4. The image for this atmospheric hole is given as Figure 1 by Frank et al. (1986c). The cometary water cloud is assumed to be positioned near the atmosphere, ~ 22,000 km from the spacecraft. The object's apparent speed is 11 km/sec and lags behind that for the scan lines by ~ 5 km/sec. Thus the consecutive scan lines can provide a coarse image of the object. The occluding disk and bright half-limb, and with the same angular dimensions, as shown in Figure 3 are superposed on the pixel map. Both features can be seen in the pixel responses. The probability that these responses are due to random events is $\lesssim 0.03$ for the entire data set used by Frank et al. (1986c). Thus, under special viewing conditions, the bright and dark features of the atmospheric holes can be spatially resolved.

A similar computational procedure is necessary to find the altitude dependence of the pixel distributions such as that shown in Figure 3. We note several important elements of this calculation. First the apparent angular size of an object of given dimensions increases with decreasing altitude. Thus the size distribution of the objects must be inferred. Secondly the area of dayglow emissions observed by the imaging instrument decreases with decreasing altitude. Thus the probability of observing a large object at low altitudes is substantially lesser than that at higher altitudes. The above two factors oppositely affect the pixel distributions such as that shown in Figure 3 when altitude variations are considered. Thus the pixel distributions are expected to be rather weakly dependent upon altitude. Still some increase in the number of consecutively darkened pixels, or double pixels, is expected with decreasing altitude. For the present data set the observed number of double pixels with averaged decreases $\leq -4\sigma$ and the expected random event rates (in parentheses) are 4(3) at 3.0 - 3.3 R_E altitudes, 12(5) at 1.5 - 2.1 R_E and 12(5) at 0.5 - 1.0 R_E. Thus the occurrence rate of double pixels at the lower altitudes is about a factor of 2 greater than the random rate. Only a relatively small increase of the rates for double pixels with decreasing altitudes in the above range is expected for the configuration of luminosity and opacity shown in Figure 3. For the present series of images the only event with three consecutively darkened pixels occurs as expected at the lowest altitudes, $\lesssim 0.3\ R_E$ (cf. Frank et al., 1986c).

Cragin et al. (1987) are unable to find any consecutively darkened pixels beyond those expected from random occurrence rates. This conclusion is based upon an incomplete theoretical treatment and an insufficiently large set of data.

In summary the conclusions of Cragin et al. (1987) that the atmospheric holes reported by Frank et al. (1986a) are not a geophysical phenomenon are shown to be incorrect due to (1) their use of an overly simplified model for the instrument responses to small, opaque objects as seen against a statistically fluctuating screen of dayglow intensities and (2) insufficiently thorough treatment of the observations. Their specific failures are noted in our presentation. Our present analyses demonstrate that the responses of the instrument provide substantial evidence that small, opaque objects with bright half-limbs are being viewed. These objects are interpreted by Frank et al. (1986b) in terms of water clouds from the disruption of small comets near the earth. Our present analyses further support the previous evidences that the atmospheric holes are a geophysical effect, e.g., the temporal variations of atmospheric hole rates and their correlation with radar meteor rates (Frank et al., 1987), the local time and latitude distribution of atmospheric holes (Frank et al., 1986a), the increase of size of atmospheric holes as seen at low altitudes (Frank et al., 1986c), the detection of atmospheric holes in consecutive imaging frames with higher temporal resolution (Frank et al., 1986a), and the organized apparent motion of atmospheric holes (Frank et al., 1986c).

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