Galileo Infrared Observations of the Shoemaker-Levy 9 G Impact Fireball: A Preliminary Report

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AIMTRACT

The Galileo spacecraft was fortuitously situated for a direct view of the impacts of the fragments of comet Shoemaker-Levy 9 in Jupiter's atmosphere. The Galileo Near Infrared Mapping Spectrometer (NIMS) instrument observed several of the impact events in several discrete bands and with a temporal resolution of roughly five seconds. Data have been received for the G impact showing two phases of strong infrared emission. The first phase is approximate] y one minute in duration and corresponds to the initial fireball and early plume development. This is followed six minutes later by the onset of heating by plume ejecta falling back on the upper atmosphere. This report provides a preliminary description of the fireball phase. The first detection of the G fireball occurred at 07:33:37 UT on July 18, 1994, approximately five seconds after the initial signal recorded by the Galileo Photopolarimeter-Radiometer instrument. The detected duration of this fireball at 4.38 μm was 70 seconds. Spectra in the first half of this period show blackbody - like emission, with absorption features from overlaying methane and molecular hydrogen. The strength of these features place the fireball in the upper troposphere and lower stratosphere, above the ammonia cloud layer. The emitting surface rises and accelerates, achieving 2 - 3 km/see after 25 seeonds, in qualitative agreement with that expected from explosions in inhomogeneous atmospheres. If the initial explosion occurred within the upper troposphere, then a small and/or low density comet fragment is indicated for the G impact event.

The Galileo spacecraft, en route to Jupiter, was situated 240 million km (1 .60 AU) from Jupiter with a spacecraft-Jupiter-Sun phase angle of 51° during the collision of Cornet Shoemaker-lzvy 9 with the planet. This geometry allowed a direct view of the impacts, which occurred on the nightside of Jupiter, not viewable from the Earth, and provided an opportunity to investigate the early temporal evolution of the impact events. It had been predicted that the comet fragments would produce high temperature bolides as they entered the atmosphere and exploded, producing a hot fireball which would rise, expand, and cool (Sekanina, 1993; Zahnle and Mac Low, 1994; Chevalier and Sarazin, 1994; Ahrens et al., 1994; Boslough et al., 1994). Much of the predicted radiation occurs in the infrared region, and time-resolved infrared spectral observations, obtained over a broad wavelength range, are ideal for studying these phenomena.

The Galileo Near Infrared Mapping Spectrometer instrument (NIMS, Carl son et al., 1992) observed the C, F, G, and R impact events, sin ultaneously with the Photopolarimeter-Radiometer (PPR) and Ultraviolet Spectrometer (UVS) instruments. At this writing, a large fraction of the G impact data has been received which describes the early evolution of the fireball. 'l'he R event data are scheduled for transmission in January 1995. It is unlikely that the data from the C and F events can be returned before Jupiter orbit insertion activities overwrite the tape on which the data reside. This brief note describes our preliminary anal ysis of the temporal development of the G impact fireball, giving the time of impact and duration, as well as illustrating some of the spectral characteristics that were observed.

At the time of the G impact, Galileo was 239. 82 x 10^6 km from Jupiter (1 .6031 AU), viewing the planet at a phase angle of 51.3". In order to ensure successful observations of the impacts, given the uncertainties in the absolute spacecraft pointing, a "chcekerboard" scan pattern was used, covering Jupiter and the immediate vicinity. The instantaneous field of view of the NIMS instrument is a square pixel with dimensions of 0.5 x 0.5 mrad (Jupiter's diameter as seen from Galileo at the time of the impacts was 0.60 mrad). Each pixel is acquired in 0.016 sec. One dimension of scanning was provided by the NIMS' scanning secondary mirror, giving a column of 20 pixels with a dimension of 10 x 0.5 mrad, acquired in 0.333 see. The spacecraft scan platform provided the sceond dimension, scanning back and forth over an angle of 3 mrad at ~0.92 mrad/see, resulting in one scan across the planet every 5 1/3 sec. Jupiter was in the field-of-view for on! y a fraction of each scan. The operation of the scan platform was as planned, with Jupiter appearing very close to the center of the scans.

The instrument was operated in the "fixed map" mode which obtains simultaneous measurements at 17 wavelengths between 0.7 and 5.0 microns for each spatial pixel. The wavelength setting was chosen to include continuum bands where Jovian atmospheric gases are transparent, and regions with differing absorption strengths so as to perform vertical sounding of the fireball in the atmosphere. The wavelength selection also included a band for possible H_3^+ emissions. For short wavelengths, the intense reflected sunlight signal from the dayside of Jupiter precludes ready identification of fireball emissions, while Jovian thermal emission obscures the fireball signature in the 5 micron region. Between these limits, in the 1.8 to 4.4 micron region, the reflected sunlight signal is weak and little atmospheric thermal emission occurs. Consequently, we employ this region for our preliminary analysis. The corresponding wavelengths and atmospheric absorption properties are listed in Table 1. The spectral resolution for each wavelength channel is 0.025 microns.

TABLE 1

N] MS Wavelengths and Jovian Atmospheric Absorption Properties

Detector No.	Wavelength (microns)	Wavenumber (cm-')	Absorber, Emitter
6	1.84	5430	Continuum
7	2.12	4710	Molecular hydrogen, pressure induced
8	2.40	4160	Methane (stratosphere)
9	2.69	3720	Continuum
10	2.97	3370	Ammonia (troposphere)
11	3.25	3075	Methane (stratosphere)
12	3.53	2830	Methane (stratosphere), H_3^+
13	3.82	2620	Methane (stratosphere)
14	4.10	2440	Continuum
15	4.38	2280	Phosphine (troposphere)

'l'he timing and duration of the G fireball is shown in Fig. 1, where we show the observed intensity at 4.38 microns as a function of time. Jupiter is normally quite dark at this wavelength owing to the weak solar flux, low reflectivity of the ammonia clouds (Drossart et al., 1982), and absorption by tropospheric phosphine. The time t = O corresponds to an earth-observed time of 07:33:37 UT, 18 July 1994. The infrared observable event could have started up to 5 1/3 sec before this time, this uncertainty due to the time resolution of the observations. The value plotted is the intensity of the fireball, considered as a point source. If it were an isotropic radiator, the luminosity (per unit wavelength) would be 4π times this quantity. Fluctuations in intensity are at least partly due to the source appearing in different positions within the instantaneous field-of-view, for which the instrument exhibits some sensitivity variations. The Galileo Photopolarimeter instrument first detected the G event at 07:33:32 UT, approximate] y 5 seconds before our first detection (Martin, 1994).

The duration of the G fireball event, as observed at this wavelength, is approximate] y one minute. The intensity peak observed at -35 sec is presumably due to the emitting area increasing with time while the fireball is cooling and the Planck function decreases in amplitude and moves to longer wavelengths. The duration and time of maximum signal would then be wavelength dependent, both increasing as the wavelength increases. Simultaneous observations of this event at 0.945 microns by the Galileo PPR (Marlin, 1994) show a duration of -35 see, with a broad maximum occurring between 5 and 10 sec after initiation, consistent with this interpretation.

It is interesting to note that the Hubble Space Telescope obtained an image of Jupiter before and during the early portion of our fireball observations (Hammel et al., 1994). The Hubble image, obtained at 0.889 microns, was a 30 sec exposure encompassing the time period

07:33:16 to 07:33:46 UT (-21 sec to +09 sec in the relative times of Fig. 1). Based on our measurements of the location of the fireball and its diameter just after this exposure (see below), the fireball would have been behind the limb of Jupiter and not directly observable from Hubble. The HST image shows a narrow, linear feature above the limb, which may be a direct detection of the incoming bolide, or a reflection of fireball radiation by accompanying dust in an extended trail (Hammel et al., 1994).

For each of the points displayed in Fig. 1 there exists a multi-channel "spectrum" corresponding to the wavelengths of Table 1. Analysis of these spectra is in the early stages, but wc show one such spectrum to illustrate their characteristics and the types of information available. The spectrum corresponding to 07:33:53 UT, 16 sec after our initial detection, is given in Fig. 2. It appears to be describable as a continuum blackbody function with superimposed absorption features. For this particular example, a reasonable fit to the shape of the continuum is a thermal source at 2,200 K. From the absolute intensity, an emitting area with diameter of 40 km (assuming sphericity) is deduced. These values must be considered tentative as we have not considered any reflection of this blackbody radiation by underlying clouds, nor have we used any sophisticated solar subtraction methods. For both of these effects, the influence is expected to be small, since the cloud-at] nosphere albedos arc generally low and there is relatively little solar flux at these wavelengths.

The strong absorption bands of methane are evident in the spectrum of Fig. 2a, as well as absorption by molecular hydrogen at 2.12 microns. We can use these absorption strengths to estimate the location of the fireball in the atmosphere. We assume that the atmosphere above the fireball is undisturbed since the bolide enters at a slant angle of -45° ; this may be an inaccurate assumption, as there could be radiative heating from the fireball in addition to heating by the shock wave of the incoming cometary fragment. We also assume that the atmospheric gas entrained in the fireball's shock region is heated sufficientl y to dissociate the molecular gases. Thus, the observed absorption pertains to the atmosphere above the shock front. Theoretical spectra for a planar source at 2,200 Kelvin and a diameter of 40 km are shown in Fig. 2b. The emission angle for the Galileo observations was 67.33°, or an airmass factor of 2.6, Calculations are shown for sources located at two pressure levels, 50 mbar and 100 mbar, and are computed for methane absorption only. All isotopes arc included in this calculation, which uses a random band model and convolves transmission spectra to the NIMS bandpass profile.

From the absorption at 3.53 and 3,84 microns, it is apparent that the effective level of the radiating surface for this spectrum is between 50 and 100 mbar. The absorption at 2.40 microns appears to be consistent with this, although this wavelength is at the edge of the absorption band and very small shifts in wavelength could introduce large variations. The 3.25 micron measurement, whose wavelength is near the center of the strong ν_3 methane fundamental band, appears to be much stronger than expected. Although this could be explained by a wavelength shift, the amount required is excessive, and we arc led to suggest that an additional source is present. In particular, we postulate band emission by methane or a hydrocarbon byproduct in the C-H stretching band occurring at higher altitudes and perhaps produced through heating by the entry shock-wave. Other possible sources include high altitude radiative heating by the fireball, or optical pumping, producing fluorescence.

As indicated in Fig. 2 there is a small amount of absorption, -25%, at the wavelength of 2.12 microns, which is expected to be mainly due to pressure induced absorption by molecular hydrogen. Using this value, the airmass factor given above, and absorption coefficients from Martin et al. (1974), we find a pressure level of 80 to 90 mbar for the source, in good agreement with the range derived from the methane absorption,

The depth of the absorption features decrease with time, and we have used the absorption depth at 3.82 μm to estimate the vertical motion of the upper emitting surface. The results are shown in Fig. 3, which indicates a rapid rise into the stratosphere, and suggests that the vertical velocity increases with time. Since we are assuming a planar source, the derived levels and velocities are approximate, but indicate supersonic velocities and therefore an associated shock wave. An accelerating supersonic shock is a characteristic of intense explosions occurring in atmospheres with vertical] y decreasing density (Kompaneets, 1960; Andriankin et al., 1962) and the acceleration observed here presumably forms at least part of the plumes which ballistically reach high altitudes (Hammel et al., 1994).

The altitudes indicated in our spectra show levels above the – 200 mbar height. Since the actual radiating surface is expected to be approximatel y spherical, the effective planar radiating level will lie somewhere between the top and center level of the fireball. If we assume that the effective surface is midway, then the center of the fireball is half a radius below the levels indicated in Fig. 3. For a 40 km diameter fireball, this corresponds to -10 km, or one half of a scale height. This places the fireball initially in the upper troposphere, just above the ammonia cloud. The lower portion of the expanding fireball could include the ammonia cloud region.

Although no evidence is found in our spectra for deeper penetration, we cannot completely rule out the possibility that the bolide penetrated the cloud region, if the clouds then obscure the radiation. However, if the ai rburst did occur in the upper troposphere, then calculations by Mac Low and Zahnle (1994) indicate a bolide diameter of < 500 meters (for a density $\rho = 0.2$ g/cm^3), or 150 meters ($\rho = 1$).

A second heating event following the G impact was observed by NIMS beginning at 07:39:41 UT. The heating continued to brighten for two minutes following initial detection, at which point our spacecraft playback of G event data was terminated. Based on relative timings from Earth-based reports, we identify this brightening as the fall back of impact ejects onto the upper Jovian at mosphere. The time interval between impact and fall back implies a minimum ejection velocity of 4.1 km/see. Analysis of the NIMS spectra of this second heating event are underway and will be reported in future publications.

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FIGURE CAPTIONS

Figure 1. Light curve for the G fireball at 4.38 microns. The apparent source intensity is given in units of 1012 Watts $sterad^{-1} \mu m^{-1}$. The first detection, at a relative time of zero, corresponds to 07:33:37 UT Earth observed time on 18 July 1994. The entire event, as seen at this wavelength, occurred over approximate] y one minute.

Figure 2. (a) A representative spectrum of the early fireball history, This spectrum corresponds to our observation 16 sec after our initial detection. A reasonable fit to the continuum is given by a 2,200 K blackbody with a 40 km diameter. Methane and molecular hydrogen absorption features arc apparent. (b) The same data shown above are compared to the blackbody source with methane absorption included. Two pressure levels are considered, the lowest curve is for a 100 mbar pressure level, the higher one is for 50 mbar. These data, and consideration of molecular hydrogen absorption (see text) indicate the fireball was located at roughly the 75 $\pm$ 25 mbar level at the time of this spectrum.

Figure 3. Atmospheric pressure levels and altitude.s for the upper surface of the fireball. A planar source was assumed and the level found from the amount of absorption by methane at 3.82 pm. Altitudes are given relative to the tropopause. The fireball appears to initiate in the upper troposphere with the upper surface rising rapid] y and accelerating, as suggested by theoretical considerations.

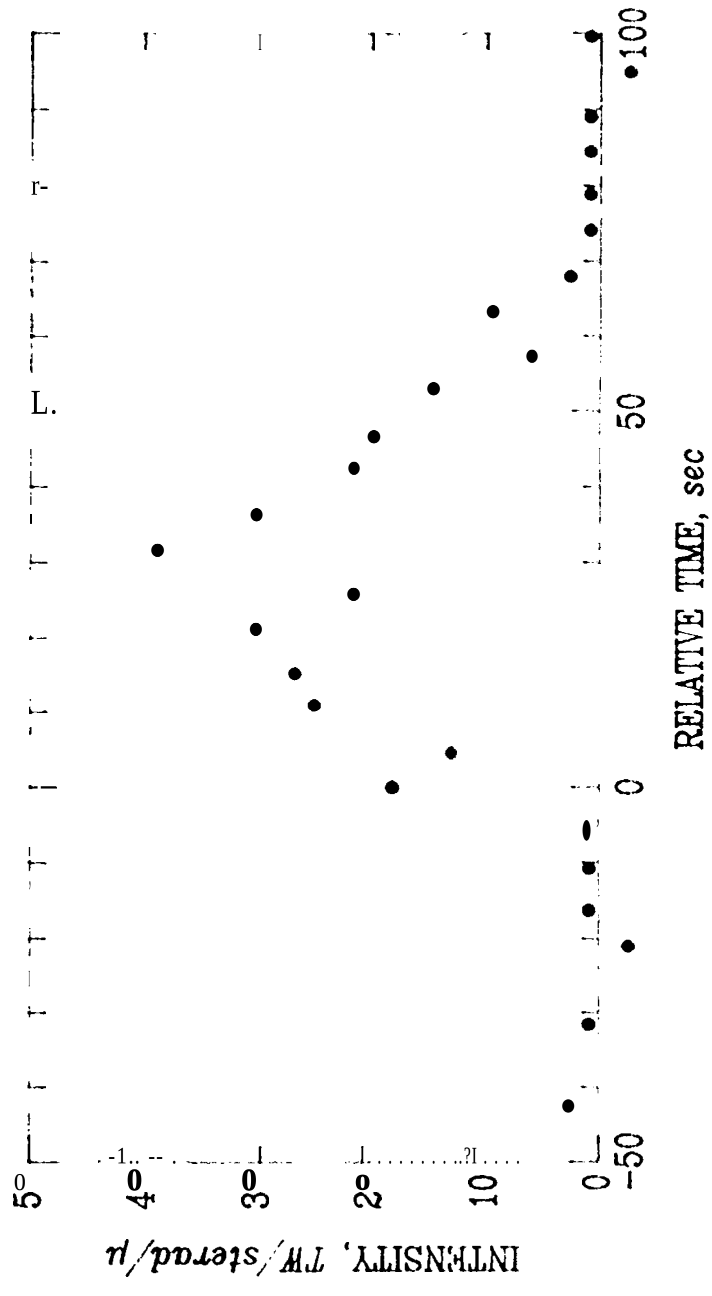

RELATIVE TIME, sec
-50
0
50
100
INTENSITY, TW/sterad/μ
0
10
20
30
40
50

Fig. 1

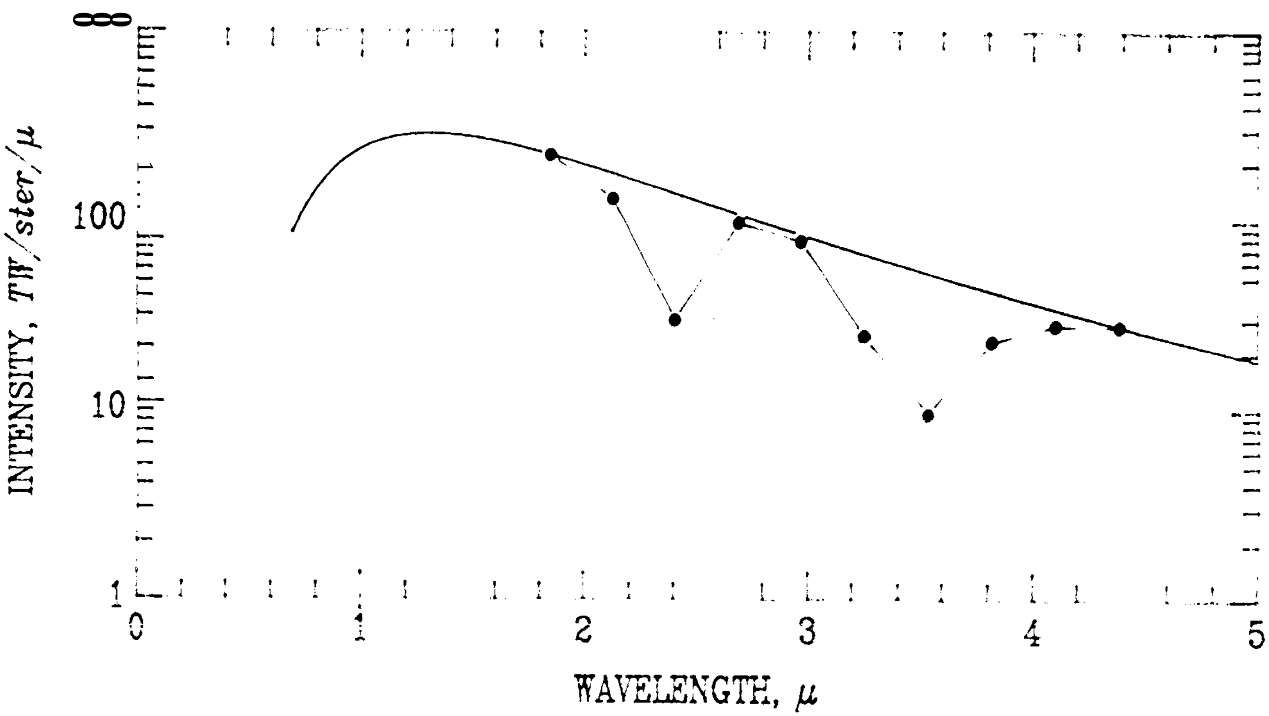


Fig. 2a

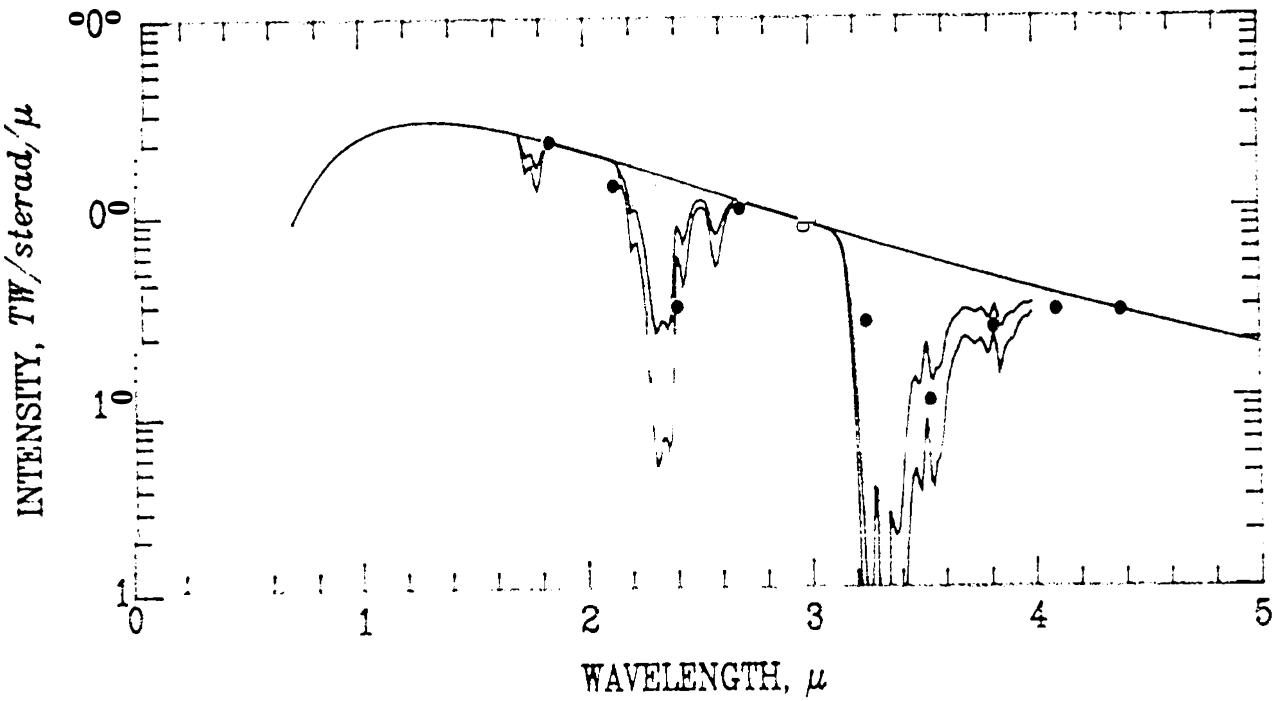
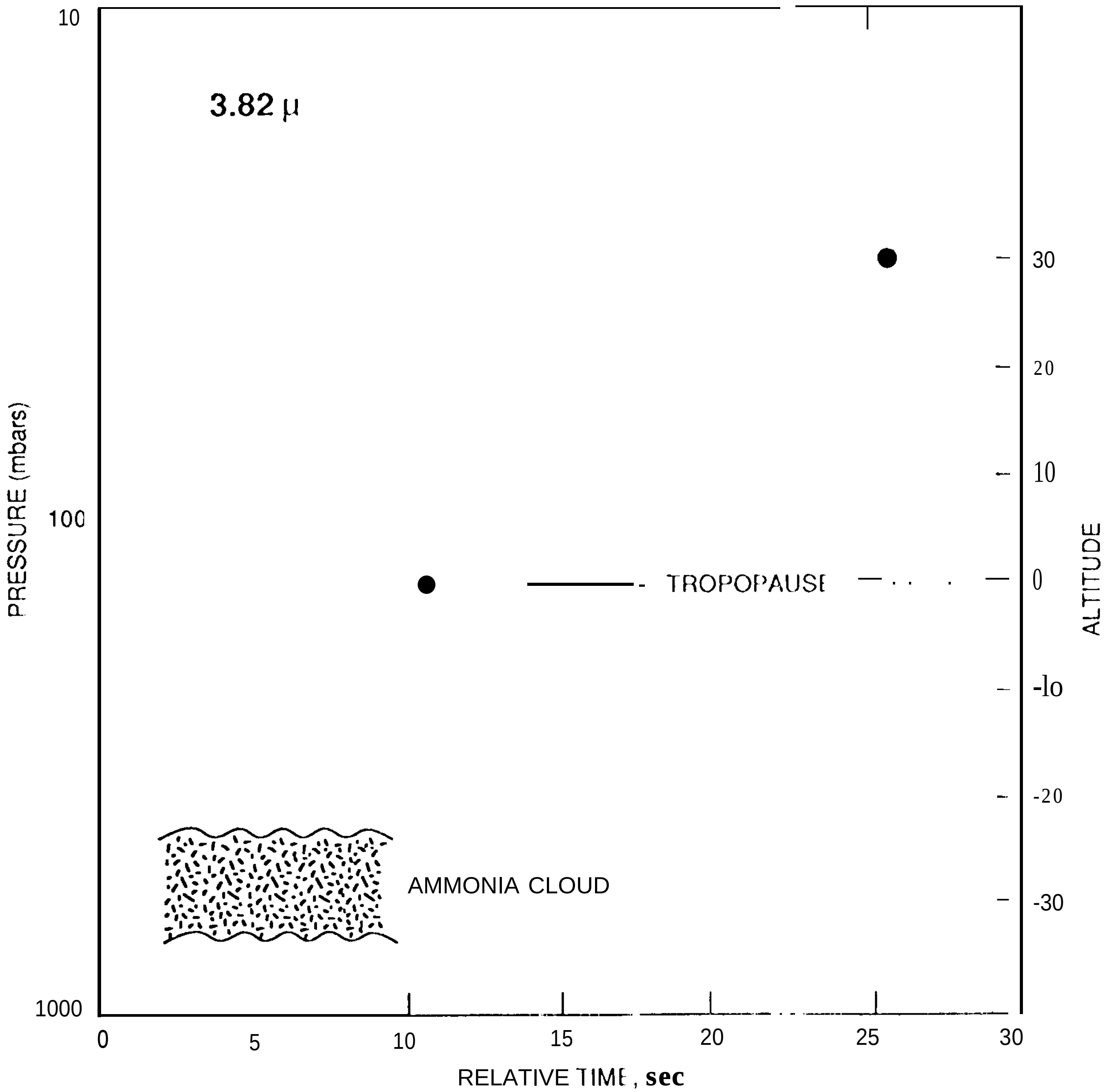


Fig 26


3.82 μ
PRESSURE (mbars)
10
100
1000
ALTITUDE
30
20
10
0
-lo
-20
-30
TROPOPAUSE
AMMONIA CLOUD
0
5
10
15
20
25
30
RELATIVE TIME, sec