THE ASTROPHYSICAL JOURNAL, 576:L95–L98, 2002 September 1

A SEARCH FOR ARGON AND O VI IN THREE COMETS USING THE *FAR ULTRAVIOLET SPECTROSCOPIC EXPLORER*

H. A. WEAVER,[1,2] P. D. FELDMAN,[1] M. R. COMBI,[3] V. KRASNOPOLSKY,[4] C. M. LISSE,[5] AND D. E. SHEMANSKY[6]
Received 2002 May 3; accepted 2002 July 23; published 2002 July 30

ABSTRACT

We conducted a sensitive search for the resonance lines of Ar I (λλ1048.22, 1066.66) and O VI (λλ1031.93, 1037.62) in the spectra of three long-period comets observed with the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*). Argon emission was *not* detected from C/1999 T1 (McNaught-Hartley), C/2001 A2 (LINEAR), or C/2000 WM1 (LINEAR). Compared with the solar value, the [Ar/O] ratio is depleted in C/A2 by at least a factor of 10 and in C/WM1 by at least a factor of 13. The [Ar/O] upper limit for C/T1 is essentially the solar value, as our measurement was much less sensitive for that case. We also detected CO, which has a volatility similar to that of argon, during the *FUSE* observations. C/T1 was CO-rich ([CO/H_2O] ≈ 13%), while both C/A2 and C/WM1 were CO-poor ([CO/H_2O] ≈ 0.7% for C/A2 and ≈0.4% for C/WM1). The argon and CO depletions in C/A2 and C/WM1 suggest formation temperatures ≳60 K for both of these comets. The high CO abundance and upper limit on the argon abundance in C/T1 suggest that its formation temperature was in the range of ∼40–50 K. No O VI emission was detected from comets C/T1 or C/A2, but the stronger line was marginally detected in C/WM1.

Subject headings: comets: general — comets: individual (C/1999 T1, C/2000 WM1, C/2001 A2) — ultraviolet: solar system

1. INTRODUCTION

Because the noble gases are both chemically inert and highly volatile, they are particularly useful for tracing the history of cometary matter and for elucidating the role played by comets in the formation and evolution of planetary atmospheres (Owen & Bar-Nun 2001). In principle, the abundances of the different noble gases (e.g., He, Ne, Ar, Kr, and Xe, in order of increasing atomic mass and decreasing volatility) can be used to constrain the thermal evolution of cometary matter, and a comparison of the noble gas abundances in comets and planetary atmospheres can be used to gauge the role of cometary bombardment in the planet's evolution. However, remote observations of the noble gases are problematic because their resonance transitions lie in the far-ultraviolet spectral region ($\lambda \leq 1200$ Å), accessible only from space and outside the wavelength range covered by the *Hubble Space Telescope* (*HST*) and the *Chandra X-Ray Observatory*.

There was a marginal detection of the two principal resonance lines of argon at 1048.22 and 1066.66 Å during a sounding rocket observation of C/1995 O1 (Hale-Bopp) in 1997, and the deduced [Ar/O] ratio was 1.8 ± 0.96 times the solar value (Stern et al. 2000).[7] Laboratory data on the capture of noble gases in water ice indicate that a solar [Ar/O] ratio can only be obtained if the equilibrium temperature of the nucleus never climbs above ∼30 K (Owen & Bar-Nun 1995). Owen & Bar-Nun (2001) suggest that the [Ar/O] ratio in most cometary nuclei should be depleted by a large factor (∼10–100) relative to the solar value, if cometary bombardment is to explain the pattern of noble gas abundances observed in the terrestrial and martian atmospheres. However, they also point out that impacts by comets having nearly solar [Ar/O] ratios are necessary to explain the noble gas pattern in the atmosphere of Venus.

The recent launch and successful deployment of the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) satellite observatory (Moos et al. 2000) enable much more sensitive searches for argon in comets than can be accomplished from rocket experiments. Following the implementation of its moving target capabilities in late-2000, we used *FUSE* during 2001 to observe three moderately bright long-period comets: C/1999 T1 (McNaught-Hartley), C/2001 A2 (LINEAR), and C/2000 WM1 (LINEAR). Over 60 new spectral features were discovered during the cometary observations with *FUSE*. A general discussion of the spectra will be presented later (H. A. Weaver et al. 2002, in preparation), and a detailed discussion of the emissions from CO and H_2 are given in Feldman, Weaver, & Burgh (2002). Here we focus on searches for argon and O VI. The O VI lines at 1031.93 and 1037.62 Å are the strongest signature of charge exchange between solar wind ions and neutral cometary species, which is thought to be the dominant excitation mechanism for X-ray emissions from comets (Lisse et al. 1999, 2001; Krasnopolsky & Mumma 2001), in the *FUSE* spectral range.

2. OBSERVATIONS

FUSE consists of four co-aligned telescopes with spectrographs, two of which have optics coated with silicon carbide (the SiC1 and SiC2 channels) and two coated with lithium fluoride over aluminum (the LiF1 and LiF2 channels). Each channel has three entrance apertures (LWRS, MDRS, and HIRS with sizes of 30″ × 30″, 4″ × 20″, and 1″.25 × 20″, respectively) that feed Rowland spectrographs having a reciprocal dispersion of 0.0062 Å pixel^{-1} in the LiF channels and 0.0067

[1] Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218; weaver@pha.jhu.edu, pdf@pha.jhu.edu.

[2] Current address: Space Department, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723-6099; hal.weaver@jhuapl.edu.

[3] Department of Atmospheric, Oceanic, and Space Sciences, 1417A Space Research Building, University of Michigan at Ann Arbor, 2455 Hayward Street, Ann Arbor, MI 48109-2143; mcombi@engin.umich.edu.

[4] Department of Physics, Catholic University of America, 620 Michigan Avenue, NE, Washington, DC 20064; vkrasn@verizonmail.com.

[5] Department of Astronomy, University of Maryland, College Park, MD 20742; lisse@astro.umd.edu.

[6] Department of Aerospace Engineering, University of Southern California, 854 West 36th Place, Los Angeles, CA 90089-1191; dons@hippolyta.usc.edu.

[7] Using $[Ar/O]_\odot = (46 \pm 8) \times 10^{-4}$, as we adopt in this Letter, the Stern et al. (Ar/O) ratio would be 1.4 ± 0.7 times the solar value. Note also that Stern et al. used $Q_O = 1.5Q_{H_2O}$, where Q refers to the species production rate, for comet Hale-Bopp, which is somewhat different than the relations adopted for the comets discussed here (see § 3).

TABLE 1
Log of *FUSE* Cometary Observations

Comet	Date (UT 2001)	Exposure Time (s) Night	Total	r (AU)	$\dot{r}$ (km s^{-1})	Δ (AU)	$\dot{\Delta}$ (km s^{-1})	ϕ (deg)	F10.7 (sfu)
C/T1	Feb 3.74–4.17	2440	15,780	1.43	+15.0	1.29	+0.56–0.89	42	144
C/A2	Jul 12.58–12.89	9530	16,485	1.20	+22.8	0.30	+14.6	46	138
C/WM1	Dec 7.37–10.01	34,577	36,557	1.12	−28.3	0.34	+13–14	58	216

Note.—The date refers the range of times over which data were taken; night refers to the total exposure time when the spacecraft was in the Earth's shadow, and total refers to the total exposure time; r and $\dot{r}$ are the comet's heliocentric distance and heliocentric radial velocity, respectively; Δ and $\dot{\Delta}$ are the comet's geocentric distance and geocentric radial velocity, respectively; ϕ is the Sun-comet-Earth angle, also called the solar phase angle; and F10.7, a solar activity index, refers to the average daily solar flux at $\lambda = 10.7$ cm at $r = 1$ AU in solar flux units (1 sfu $= 10^{-22}$ W m^{-2} Hz^{-1}).

Å pixel^{-1} in the SiC channels. For each cometary observation, the nucleus was centered in the LWRS aperture using an onboard acquisition sequence that centroided the brightness in the cometary continuum,[8] and the telescope was commanded to track at the cometary rate of motion. The jitter about the comet's track was less than ~1″.5. All data were taken in time-tag mode with a resolution of 1 Hz and were processed using the CALFUSE version 2.0.5 calibration software. The absolute fluxes derived from *FUSE* spectra have an accuracy of ~10%. The wavelength scale was adjusted to a cometocentric frame and should be accurate to ~5 km s^{-1}. Further discussion of the technical aspects of *FUSE* can be found in Sahnow et al. (2000).[9]

Table 1 lists the observing circumstances for the *FUSE* cometary investigations. C/1999 T1 has an orbital period of ~580,000 yr but is definitely *not* making its first trip to the inner solar system from the Oort cloud (B. Marsden 2001, private communication). No significant temporal variability was detected by other observers near the time of the *FUSE* observations (N. Biver 2002, private communication; Bergin et al. 2001), although some spectral variability was seen (Lynch et al. 2001). We observed C/T1 with *FUSE* during five consecutive orbits. As the primary purpose was to test the ability of *FUSE* to acquire and track cometary targets, these observations were conducted under conditions that were not optimal for a scientific investigation. Most of the data were accumulated during the daytime portion of the orbit and suffer some contamination from terrestrial dayglow emissions (Feldman et al. 2001).

[8] The Fine Error Sensor, or FES, is a CCD camera with an *R*-band filter.
[9] See also http://fuse.pha.jhu.edu/support/guide/obsguide.html.

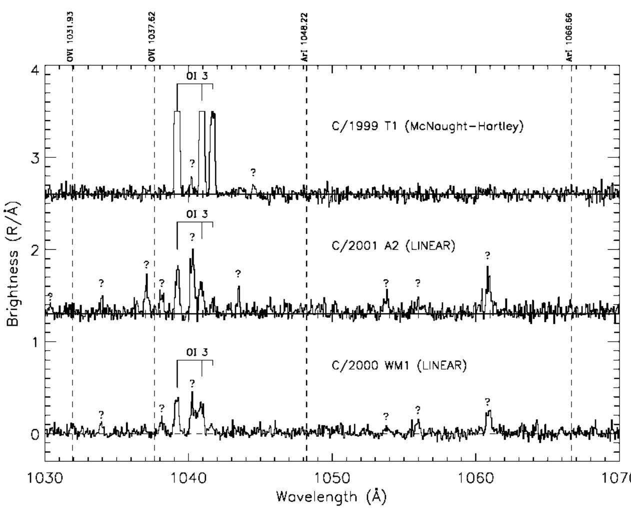

Fig. 1.—*FUSE* spectra of three long-period comets: C/1999 T1 (McNaught-Hartley), C/2001 A2 (LINEAR), and C/2000 WM1 (LINEAR). Data from the LiF1 and LiF2 channels were weighted by the effective areas of each channel and then averaged. Only the region in the vicinity of the Ar I and O VI lines is plotted; the dashed vertical lines mark the predicted locations of these lines. The original spectra were rebinned from 16,384 pixels to 2048 pixels and further smoothed by a 3 pixel running average. A spline fit was used to remove a background level that varied slowly with wavelength in the spectrum of C/1999 T1. The effective exposure times were 15,780 s for C/1999 T1 (of which 2440 s was during orbital night), 9530 s for C/2001 A2 (night-only data), and 34,577 s for C/2000 WM1 (night-only data). The spectra of C/A2 and C/T1 are divided by a factor of 1.5 and displaced vertically for clarity. There is a marginal detection (3.8 σ) of the O VI line near 1032 Å in the spectrum of C/2000 WM1, but otherwise no Ar I and O VI emissions are observed. Cometary emission in the O I 3 multiplet is observed near 1040 Å (it is mostly terrestrial airglow for C/1999 T1), and there are several other unidentified, but real, cometary emissions (marked by ?).

C/2001 A2 has an orbital period of ~33,000 yr and displayed erratic activity during the spring and summer of 2001, including the ejection of several fragments (Sekanina et al. 2002). *FUSE* observed C/A2 for five consecutive orbits following a major outburst on 2001 July 12. The brightness of the CO (0, 0) band in the *C–X* system decreased by nearly a factor of 2 during the course of the *FUSE* observations, and the continuum brightness declined by ~30% over the same period (Feldman et al. 2002). For the results presented here, we simply averaged all of the data. Over 60% of the data were obtained during the nighttime portion of the orbit, and we focus on those because they are nearly free of terrestrial airglow emissions.

C/2000 WM1 has an orbital period of roughly 85,000 yr and was exceptionally bright at the time of its discovery in 2000 November near $r \sim 6$ AU. C/WM1 was well placed for *FUSE* observations near the time of its closest approach to Earth in early December of 2001, and we observed the comet for a total of 21 orbits over several days. Almost 95% of the C/WM1 data were obtained at night, and we report here on those data only. The comet's activity was remarkably stable during the *FUSE* observations: neither the continuum brightness, as determined from the FES images taken every orbit, nor the stronger ultraviolet emissions varied by more than a few percent. Thus, we present only the average spectrum over the entire observing period.

3. SPECTRA AND DISCUSSION

A small portion of the average *FUSE* spectra in the wavelength region covering the expected positions of the argon and O VI lines is displayed in Figure 1. There is no evidence of argon emission in any of the three comets (Table 2), although several other cometary features were detected. The O VI line at 1031.93 Å, which should be ~2 times stronger than the O VI line at 1037.62 Å under optically thin conditions,

TABLE 2
LINE BRIGHTNESSES

Comet	Argon B_{1048}	Argon B_{1066}	O VI B_{1032}	O VI B_{1038}
C/T1	-0.004 ± 0.011	0.021 ± 0.012	0.016 ± 0.011	-0.005 ± 0.011
C/A2	0.026 ± 0.013	0.041 ± 0.017	0.032 ± 0.014	0.019 ± 0.012
C/WM1	0.006 ± 0.007	0.005 ± 0.008	0.030 ± 0.008	0.004 ± 0.007

NOTE.—The brightnesses (B) refer to average values in a $30'' \times 30''$ aperture [in units of rayleighs; 1 R $= 10^6$ photons cm^{-2} s^{-1} $(4\pi$ sr$)^{-1}$].

was marginally detected in C/WM1 (Table 2) but not in C/A2 or C/T1.

Our analysis of the O VI emission assumes that the principal excitation mechanism is charge exchange between O VII solar wind ions and cometary H_2O molecules and that all of the O VII ions undergo charge exchange at the small cometocentric distances (≤15,000 km) primarily sampled by the *FUSE* LWRS aperture. We used the results from Kharchenko & Dalgarno (2001) for the quantum yield of O VI emission at 1031.93 Å (∼0.3), the data from Schwadron & Cravens (2000) for the O VII flux in the solar wind (∼1.1×10^5 cm^{-2} s^{-1} at $r = 1$ AU), and scaled the intensities by r^{-2} to estimate the brightness in O VI λ1031.93 Å for each comet. We predict 0.016, 0.023, and 0.026 R for comets C/T1, C/A2, and C/WM1, respectively. *Chandra* observations of C/T1 (Krasnopolsky et al. 2002) during 2001 January 8–14 at $r \sim 1.26$ AU gave a brightness of 0.055 R for $E > 150$ eV near the nucleus. The O VI emission at 1031.93 Å should be ∼0.17 times this X-ray emission (V. Kharchenko 2002, private communication), or ∼0.009 R at that time. Scaling this result by r^{-2}, we would expect ∼0.007, 0.010, and 0.012 R of O VI emission for the *FUSE* observations of C/T1, C/A2, and C/WM1, respectively. These two different approaches for estimating the O VI emission are in good agreement considering the model and measurement uncertainties, and both are consistent with our *FUSE* results.

We used the 5 σ upper limit for the brightness (B) of the argon line at 1048.22 Å (Table 2) and the g-factor for the line[10] to calculate the aperture-averaged column density (N) of argon using $B = gN/r^2$. We used a standard Haser model (Haser 1957), with an outflow velocity of $0.8/\sqrt{r}$ km s^{-1} and an argon lifetime of $1.5 \times 10^6 r^2$ s (Huebner, Keady, & Lyon 1992), to find the corresponding upper limit on the argon production rate (Q_{Ar}). For all the g-factors used in this Letter, we assume that resonant scattering of the solar flux is the only excitation mechanism. We used the high-resolution, disk-averaged solar spectrum from the Solar Measurement of Emitted Radiation (SUMER) instrument (Curdt et al. 2001) on the *Solar and Heliospheric Observatory* (*SOHO*) spacecraft to determine the solar flux at the cometary absorption wavelength (i.e., we accounted for $\dot{r}$). Since the SUMER spectrum was obtained under solar minimum conditions, we scaled the solar fluxes upward by a factor that depends on the average solar activity index (Table 1) during the time of the *FUSE* observations (Richards, Fennelly, & Torr 1994a, 1994b). For comets C/T1 and C/A2, the scale factor was 1.3, and for C/WM1 the scale factor was 1.6.

[10] Under optically thin conditions, the argon line at 1048.22 Å is expected to be 1.5–1.7 times brighter than the line at 1066.66 Å, depending on the heliocentric radial velocity.

The abundance ratio [Ar/O] is of particular interest because of its relevance to the possible contribution of cometary impacts to the volatile inventory of the terrestrial planets (Owen, Bar-Nun, & Kleinfeld 1992; Owen & Bar-Nun 1993, 1995, 1996, 2001; Owen 2001). We calculate the [Ar/O] ratio by first estimating the [Ar/H_2O] ratio and then make a correction for other possible contributors to oxygen in the comet.

There are several independent estimates of Q_{H_2O} in C/T1 near the time of the *FUSE* observations. Direct observations of a pure rotational line of H_2O by the *Submillimeter Wave Astronomical Satellite* (*SWAS*) yields $Q_{H_2O} = (4 \pm 1) \times 10^{28}$ s^{-1} for the average of three observations (2001 February 3.9, 5.6, and 6.6) during which time no temporal variability was detected (E. Bergin 2001, private communication). Radio observations of HCN give $Q_{HCN} = (4.8 \pm 0.6) \times 10^{25}$ s^{-1} averaged over the period from 2001 January 24 to February 7, which is consistent with the *SWAS* result if the [HCN/H_2O] ratio is the "typical" value of ∼0.1% (N. Biver 2002, private communication). Measurements of H I Lyα emission by the Solar Wind ANisotropies (SWAN) instrument on the *SOHO* spacecraft yielded estimates for Q_{H_2O} of $(7.6 \pm 0.8) \times 10^{28}$ s^{-1} on 2001 February 3.343 and $(6.8 \pm 0.7) \times 10^{28}$ s^{-1} on 2001 February 4.401, where the quoted error includes an estimated systematic component of ∼10% (T. Makinen 2002, private communication). Taking into account this spread of values, we conservatively adopt a value for Q_{H_2O} of $(5 \pm 2) \times 10^{28}$ s^{-1} (Table 3). Given the high [CO/H_2O] ratio observed in C/T1 (Biver et al. 2001; Mumma et al. 2001; Feldman et al. 2002) (see Table 3), and the possibility of a significant contribution of oxygen from CO_2, which could not

TABLE 3
g-FACTORS AND PRODUCTION RATES

Comet	g_{1048} ($\times 10^{-8}$ photons s^{-1})	g_{1066} ($\times 10^{-8}$ photons s^{-1})	Q_{Ar} ($\times 10^{25}$ s^{-1})	Q_{CO} ($\times 10^{26}$ s^{-1})	Q_{H_2O} ($\times 10^{28}$ s^{-1})	[CO/H_2O] (%)	[Ar/O] ($\times 10^{-4}$)
C/T1	11	7.5	≤22	64	5.0 ± 2.0	13	≤42 ± 10
C/A2	9.7	5.8	≤5.2	13	20 ± 10	0.65	≤2.4 ± 1.2
C/WM1	11	6.5	≤2.5	3.2	8.0 ± 1.0	0.40	≤2.8 ± 0.3

NOTE.—The g-factors are per molecule at $r = 1$ AU and include only resonant scattering of sunlight adjusted for the solar activity on the date of the observations. The argon production rates (Q_{Ar}) and argon-to-oxygen abundance ratios ([Ar/O]) are 5 σ upper limits. The CO production rates (Q_{CO}) are taken from Feldman et al. 2002 and P. D. Feldman 2002, private communication, and may be uncertain by as much as a factor of ∼2. The H_2O production rates (Q_{H_2O}) are discussed in the text; $[Ar/O]_\odot = (46 \pm 8) \times 10^{-4}$ (Grevesse & Sauval 1998; Sofia & Meyer 2001a, 2001b).

be observed, we adopted $Q_O = 1.3Q_{H_2O}$, which leads to the value of [Ar/O] listed in Table 3.

As previously mentioned, we observed C/A2 shortly after a major outburst in activity, and we list only the average values for the brightnesses and production rates (Tables 2 and 3). *SWAS* observed C/A2 on 2001 July 13.15, 13.22, and 13.94, i.e., shortly after the *FUSE* observations, and the derived average value for Q_{H_2O} is $(6 \pm 2) \times 10^{28}$ s^{-1} (D. Bockelée-Morvan 2002, private communication). We adopt a larger value of $(2 \pm 1) \times 10^{29}$ s^{-1} derived from the *FUSE* measurements of several H_2, H I, and O I lines, all of which yield consistent values for Q_{H_2O} (H. A. Weaver et al. 2002, in preparation). The observed [CO/H_2O] ratio of ~0.7% (Feldman et al. 2002) is rather low, so we conservatively adopted $Q_O = 1.1Q_{H_2O}$, assuming that up to ~9% of O in the coma could be contributed by unobserved CO_2 (Feldman et al. 1997).

Several space- and ground-based campaigns were mounted to observe C/WM1 during November and December of 2001. *HST* observations of OH emission during UT 2001 December 8–11 demonstrated that the activity of the comet was remarkably stable, with no detectable temporal variations larger than ~5%, and that the derived water production rate was $(8.0 \pm 1.0) \times 10^{28}$ s^{-1} (H. A. Weaver et al. 2002, in preparation). SWAN/*SOHO* observations of H Lyα emission on UT 2001 December 6.769 and 11.609 yield $Q_{H_2O} = (9.54 \pm 0.07) \times 10^{28}$ s^{-1} and $(9.37 \pm 0.06) \times 10^{28}$ s^{-1}, respectively (T. Makinen 2002, private communication). The light curve measured with the *FUSE* FES, using a synthetic aperture of $7''.5 \times 7''.5$, was stable at the 2% level over the entire observing period, and the water production rate derived from several H_2, H I, and O I lines yielded $Q_{H_2O} = (8 \pm 1) \times 10^{28}$ s^{-1}. We adopt this latter value for the entire period of the *FUSE* observations. The [CO/H_2O] ratio in C/WM1 was ~0.4% (Table 3), so we adopted $Q_O = 1.1Q_{H_2O}$, as we did for C/A2.

The derived upper limits for [Ar/O] (Table 3) show strong depletions, relative to the solar abundance, in comets C/A2 and C/WM1. These depletions, together with the observed [CO/H_2O] ratios and laboratory data on the sublimation behavior of ices (Notesco, Laufer, & Bar-Nun 1997), suggest a formation temperature ≥60 K for both of these cometary nuclei. The much higher CO abundance for C/T1 and the upper limit on the [Ar/O] ratio suggest that this comet's nucleus formed at a temperature between 40 and 50 K. Of course, these conclusions on the formation temperatures rest on the assumption that the laboratory experiments on ices accurately reflect the trapping of gases in cometary nuclei, which may not be valid. What is clear, however, is that *FUSE* observations provide a sensitive probe of argon in comets. Observations of future moderately bright comets under favorable conditions will be especially interesting for a comet with a high CO abundance, which presumably indicates a particularly cold formation environment.

Since the presence of line emission clearly distinguishes the charge-exchange model from other potential mechanisms for producing X-ray emissions in comets (Krasnopolsky 1997; Lisse et al. 1999), and since the spectral resolving power of *FUSE* is ~100 times higher than for the *Extreme Ultraviolet Explorer* and ~1000 times higher than for *Chandra*, the *FUSE* detection of O VI line emission can potentially provide critical evidence for or against the charge-exchange excitation model. Unfortunately, the poor signal-to-noise ratio of the O VI detection in C/WM1 prevents definitive conclusions to be drawn in this case, but future observations of brighter comets should be more illuminating.

We are grateful for the excellent work by the *FUSE* ground system personnel in planning and executing these difficult observations, particularly B. Roberts, T. Ake, A. Berman, B. Gawne, and J. Andersen. We thank T. Owen for valuable discussions and E. Bergin, N. Biver, D. Bockelée-Morvan, J. Crovisier, T. Makinen, and D. Schleicher for communicating their results on production rates prior to publication. Financial support for this work has been provided by NASA through grant NAG5-10921 (*FUSE* Guest Investigator program B050) and contract NAS5-32985 (*FUSE* Guaranteed Time Team program P180). The NASA-CNES-CSA *FUSE* mission is operated by Johns Hopkins University.

REFERENCES

Bergin, E. A., Neufeld, D. A., Kleiner, S. C., Wang, Z., & Melnick, G. J. 2001, IAU Circ. 7596
Biver, N., Bockelee-Morvan, D., Crovisier, J., Lis, D. C., & Weaver, H. 2001, IAU Circ. 7559
Curdt, W., Brekke, P., Feldman, U., Wilhelm, K., Dwivedi, B. N., Schühle, U., & Lemaire, P. 2001, A&A, 375, 591
Feldman, P. D., Festou, M. C., Tozzi, G. P., & Weaver, H. A. 1997, ApJ, 475, 829
Feldman, P. D., Sahnow, D. J., Kruk, J. W., Murphy, E. M., & Moos, H. W. 2001, J. Geophys. Res., 106, 8119
Feldman, P. D., Weaver, H. A., & Burgh, E. B. 2002, ApJ, 576, L91
Grevesse, N., & Sauval, A. J. 1998, Space Sci. Rev., 85, 161
Haser, L. 1957, Bull. Acad. R. Sci. Liège, 43, 740
Huebner, W. F., Keady, J. J., & Lyon, S. P. 1992, Ap&SS, 195, 1
Kharchenko, V., & Dalgarno, A. 2001, ApJ, 554, L99
Krasnopolsky, V. 1997, Icarus, 128, 368
Krasnopolsky, V., Christian, D. J., Kharchenko, V., Dalgarno, A., Wolk, S. J., Lisse, C. M., & Stern, S. A. 2002, Icarus, in press
Krasnopolsky, V. A., & Mumma, M. J. 2001, ApJ, 549, 629
Lisse, C. M., et al. 1999, Icarus, 141, 316
Lisse, C. M., Christian, D. J., Dennerl, K., Meech, K. J., Petre, R., Weaver, H. A., & Wolk, S. J. 2001, Science, 292, 1343
Lynch, D. K., Russell, R. W., Kim, D., Sitko, M. L., & Brafford, S. 2001, IAU Circ. 7582
Moos, H. W., et al. 2000, ApJ, 538, L1
Mumma, M. J., Dello Russo, N., DiSanti, M. A., Magee-Sauer, K., Novak, R., Conrad, A., & Chaffee, F. 2001, IAU Circ. 7578
Notesco, G., Laufer, D., & Bar-Nun, A. 1997, Earth Moon Planets, 77, 237
Owen, T. C. 2001, Meteoritics Planet. Sci., 36, 156
Owen, T., & Bar-Nun, A. 1993, Nature, 361, 693
———. 1995, Icarus, 116, 215
———. 1996, Earth Moon Planets, 72, 425
———. 2001, Origins Life Evol. Biosphere, 31, 435
Owen, T., Bar-Nun, A., & Kleinfeld, I. 1992, Nature, 358, 43
Richards, P. G., Fennelly, J. A., & Torr, D. G. 1994a, J. Geophys. Res., 99, 8981
———. 1994b, J. Geophys. Res., 99, 13,283
Sahnow, D. J., et al. 2000, ApJ, 538, L7
Schwadron, N. A., & Cravens, T. E. 2000, ApJ, 544, 558
Sekanina, Z., Jehin, E., Boehnhardt, H., Bonfils, X., Schuetz, O., & Thomas, D. 2002, ApJ, 572, 679
Sofia, U. J., & Meyer, D. M. 2001a, ApJ, 554, L221
———. 2001b, ApJ, 558, L147
Stern, S. A., Slater, D. C., Festou, M. C., Parker, J. W., Gladstone, G. R., A'Hearn, M. F., & Wilkinson, E. 2000, ApJ, 544, L169