THE DISCOVERY OF ARGON IN COMET C/1995 O1 (HALE-BOPP)

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ABSTRACT

On 1997 March 30.14, we observed the EUV spectrum of the bright comet C/1995 O1 (Hale-Bopp) at the time of its perihelion, using our Extreme Ultraviolet Spectrograph sounding-rocket telescope/spectrometer. The spectra reveal the presence H Lyβ, O+, and, most notably, argon. Modeling of the retrieved Ar production rates indicates that comet Hale-Bopp is enriched in Ar relative to cosmogonic expectations. This in turn indicates that Hale-Bopp’s deep interior has never been exposed to the 35–40 K temperatures necessary to deplete the comet’s primordial argon supply.

Subject headings: comets: general — comets: individual (Hale-Bopp 1995 O1) — solar system: formation

1. INTRODUCTION

As well-preserved ancient relics of the chemistry present at the formation stage of the outer solar system, comets provide one of the most valuable tools available for understanding the formation processes and conditions extant when the planets formed ≈4.5 Gyr ago (Mumma, Weissman, & Stern 1993). Among the most long-standing observational goals for understanding cometary origins has been the search for cometary noble gases. Owing to their combination of high volatility and disaffinity to chemical reactions, noble gases provide a key diagnostic to the thermal history of cometary ices. More specifically, the members of the He, Ne, Ar, Kr sequence display successively higher sublimation temperatures; as such, they provide a series of thermometers that can be exploited to constrain the thermal history and therefore the sites of cometary origins.

Although the interpretation of noble gas abundances in cometary comae is complicated by the details of their trapping and release efficiencies in cometary ice (Owen, Bar-Nun, & Kleinfeld 1991), their detection has nonetheless been highly desired. Unfortunately, however, although significant upper limits revealing He depletions of ~10⁶ in comet Austin (Stern et al. 1992) and Ne depletions of ~25 in comet Hale-Bopp (Krasnopolksy et al. 1997) have been obtained, no detection of any cometary noble gas emanating from within a comet has previously been obtained.

He, Ne, Ar, and Kr each have resonance transitions in the far- and extreme-ultraviolet. Among the noble gases, argon offers a particularly good combination of comparatively high cosmogonic abundance, moderate sublimation temperature, and good UV resonance fluorescence efficiency; together, these properties suggested some time ago (Stern et al. 1992; Mumma et al. 1993) that argon may be the easiest noble gas to detect in comets. We took advantage of the apparition of the unusually active and bright comet C/1995 O1 (Hale-Bopp) in order to conduct a new and more sensitive search for argon in comets.

2. THE 950–1100 Å SPECTRUM OF COMET HALE-BOPP

With the objectives of (1) obtaining a general survey spectrum of Hale-Bopp in the EUV near its perihelion and (2) making a more sensitive search for argon than had previously been attempted for any comet, we launched the Extreme Ultraviolet Spectrograph (EUVS) sounding-rocket telescope/spectrometer payload on a suborbital mission timed to coincide with the comet’s perihelion. This timing also corresponded closely to the epoch of Hale-Bopp’s peak in activity.

The 184 kg EUVS payload (Slater et al. 1995) consists of a 40 cm diameter grazing-incidence telescope, a long-slit Rowland circle spectrograph, and its accompanying Ranicon twodimensional microchannel plate detector, power system, and telemetry electronics. The telescope is a diamond-turned f/15 Wolter type II grazing-incidence design with a 30 cm aperture (Cash et al. 1989). The primary mirror is Ni coated; the secondary is SiC coated. For the Hale-Bopp flight, EUVS was configured to study the bandpass from 820 to 1100 Å; the characteristic effective area of the instrument in this bandpass is 0.5 cm².

EUVS was launched to observe Hale-Bopp on a NASA Black Brant IX sounding rocket from White Sands, New Mexico, at 03:25 UT on 1997 March 30. At this time, Hale-Bopp was less than 48 hr from perihelion, with a geocentric distance of Δ = 1.34 AU, a heliocentric distance of R = 0.915 AU, and a heliocentric radial velocity of V = −1.20 km s⁻¹. The launch occurred in darkness, with the Sun and the comet 116° and 76° from the zenith, respectively. The launch vehicle performed nominally, lifting the instrument to a peak altitude of 314 km. During the flight, EUVS remained in the Earth’s shadow at all times; the line of sight to the comet remained above local horizontal. These two factors effectively eliminated telluric dayglow emissions from the spectra that EUVS obtained. The data that we describe below were obtained during the 195 s period when the payload was above 200 km, where telluric absorption of the EUV is also negligible (Paxton & Anderson 1992).

EUVS successfully obtained spectra for surveying Hale-Bopp in the EUV bandpass using both its 130×386’ (12.5 Å) medium-resolution (MRES) EUVS and 130×65’ (2 Å) high-resolution (HRES) EUVS slits; the centers of these two slits are located 130° apart. Based on count rate measurements received...
in real time as telemetry, we elected to maximize the signal-to-noise ratio at the expense of the spectral resolution and to place the center of brightness of Hale-Bopp’s coma in the MRES; the adjacent HRES slit was therefore located some $1.27 \times 10^3$ km away, along the tail axis of the comet. The EUVS Hale-Bopp data set contains both strong H Ly$\beta$ and the first ever spectroscopic detections of other neutral H and O features in the EUV, cometary O$^+$, and cometary argon (Stern et al. 1998). In this Letter, we concentrate on the 950–1100 Å portion of the EUVS data (see Fig. 1) in order to focus on the evidence for, and implications of, Ar in Hale-Bopp; a future publication will discuss the other emissions in the EUVS Hale-Bopp data set.

The EUVS wavelength scale was established by a least-squares fit to a series of Pt-lamp lines imaged onto the detector before and after the flight; these pre- and postflight wavelength calibrations concurred to within 3 Å. During data reduction, accurate coregistration of the wavelength scales for the MRES and HRES data was achieved using the centroid of the prominent 1025.7 Å Ly$\beta$ emission line in Hale-Bopp. The effective area of EUVS was calibrated in flight as a function of wavelength using the UV-bright B0.5 IV star Persei. A postflight laboratory effective area calibration was also obtained, using an O$^+$/Ar resonance source at five wavelengths across the EUVS bandpass. The two calibrations are in good ($\pm 35\%$) agreement.

Using the effective area of the instrument and the solid angle of the slit(s), we converted the Hale-Bopp raw count spectra to the brightness spectra shown in Figure 1. The brightness error bars shown in Figure 1 were computed at each plotted wavelength using the UV-bright B0.5 IV star Persei. A postflight laboratory effective area calibration was also obtained, using an O$^+$/Ar resonance source at five wavelengths across the EUVS bandpass. The two calibrations are in good ($\pm 35\%$) agreement.

The MRES data in Figure 1 reveal what we believe are the 1048 and 1066 Å Ar i features blended together just redward of the far stronger 1026 Å H i/o i blend. Additional emissions are seen between 975–990 Å and 1080–1097 Å. Although these emissions are clearly statistically significant, their identification is not presently secure; therefore, the analysis of these emissions and the marginally optically thick H Ly$\beta$ signal that EUVS detected will be discussed in a second publication. Regarding the latter, here we simply note that the Ly$\beta$ feature is blended with a contribution from an O i (3$d^2$3$D_{1,2,0} \rightarrow 2s^22p^4P_{3,1,0}) triplet at 1025.7, 1027.4, and 1028.7 Å, which, owing to radiative pumping by Ly$\beta$, is difficult to model precisely but which, to first order, contributes $\sim 15$ R; the telluric background Ly$\beta$ brightness is estimated to contribute some 20 R above the background. Sky background spectra obtained while EUVS was maneuvering toward Hale-Bopp contain only a weak instrumental background and H i Ly$\beta$ emission generated by a combination of geocoronal and interplanetary medium hydrogen. The fact that no other features are present in EUVS sky background spectra, combined with the observing altitude and geometry discussed above, virtually eliminates the possibility that the features seen at Hale-Bopp are due to telluric contamination.

Returning now to the main subject of this Letter, additional evidence for the Ar identification comes in three forms. First, the width of the MRES feature extending from 1045 to 1070 Å is consistent with a pair of blended lines 19 Å apart (such as the two Ar lines). Second, the sense of the asymmetry seen in the 1045–1070 Å emission is consistent with the fact that the 1048 Å line’s resonance fluorescence efficiency in sunlight (i.e., its g-factor) is 2.4 times higher than the 1066 Å line’s. Third, as shown in the right-hand panel of Figure 1, there is also clear evidence for a 1048 Å Ar feature (present some 3.2σ above the local background) and a hint of the 1066 Å feature in the higher resolution EUVS data, thereby all but eliminating pathological (i.e., false) detection cases (e.g., due to flat-field effects or counting statistics variations) of the Ar features in the main slit.

Since the MRES data have considerably better count levels than the HRES data, we used our line-detection software to retrieve individual, background-subtracted Gaussians (with widths established from calibration line sources) for the two suspected MRES data set argon features. This software, which obtains best-fit wavelengths and integrated brightness Gaussians for features detected above a specified background, retrieved brightnesses and statistical error bars of $24 \pm 8$ R centered at 1049 Å and $12 \pm 5$ R at 1066 Å (1 R = $10^6$ photons cm$^{-2}$ s$^{-1}$ emitted into 4π sr). It is worth pointing out that the $2.0 \pm 0.6$ ratio of these two retrieved brightnesses corresponds well (within our statistics) to the 2.4 : 1 value predicted by their
g-factors and the line-formation theory for optically thin emission.⁶

3. ARGON AND ITS IMPLICATIONS

In order to interpret the Ar emissions, we first converted the signal brightness \( B \) in rayleighs into a slit-average column density \( N \) along the line of sight for each Ar line.⁷ The conversion to column densities in the slit was performed according to the optically thin approximation: \( N_i = \frac{10^5 B_i}{g_i} \), where \( B_i \) is the brightness of line \( i \) and \( g_i \) is the photon fluorescence rate (i.e., in units of photons s⁻¹) of that emission at the comet. We adopted resonance fluorescence efficiencies at 1 AU of \( 5.3 \times 10^{-8} \) s⁻¹ and \( 2.2 \times 10^{-8} \) s⁻¹ for the 1048 and 1066 Å lines, respectively (after adjustment for the variation in solar FUV using the daily F10.7 solar flux index at the time of our flight); these \( g \)-values (derived from Meier 1991 and Parker et al. 1998) were then adjusted to reflect Hale-Bopp’s 0.915 AU heliocentric distance.

To derive an Ar production rate \( Q_\text{Ar} \), we constructed a simple model of the coma’s Ar distribution, assuming a spherically symmetric, steady state radial outflow diverging from a point source. To calculate \( Q_\text{Ar} \), we assumed an argon outflow velocity in equilibrium with the H₂O outflow, i.e., \( v_i = 1.25 \text{ km s}^{-1} \) at 0.915 AU. Based on the MRES slit brightnesses (and counting + background brightness errors) of the two argon lines, an error-weighted average Ar production rate of \( (1.1 \pm 0.3) \times 10^{20} \text{ s}^{-1} \) was derived.

To interpret the physical meaning of the EUVS Ar production rate obtained above, we took the ratio of the derived Ar production rates to the O production rate of the comet. H₂O is the dominant O-bearing molecule in cometary ices, so we derived the O production rate \( Q_\text{O} \), using the established 1.1 \( \times 10^{27} \) s⁻¹ perihelion H₂O production rate (Biver et al. 1997; Colom et al. 1997). To account for the oxygen in other O-bearing species (CO, CO₂, CHON, SiO) when deriving the Ar/O production ratio, we adopt \( Q_\text{Ar}/Q_\text{O} = 1.5Q_{\text{H}_2\text{O}} \) (based on Giotto NMS data adjusted for the higher CO abundance of Hale-Bopp; W. Huebner 2000, private communication). Based on this and the \( Q_\text{Ar} \) estimate given above, we thus derive an estimate of \( [\text{Ar}/\text{O}] = 0.0058 \pm 0.0017 \) in Hale-Bopp’s coma. In what follows, we assume that this ratio of production rates is indicative of the coma’s Ar/O abundance ratio. The most recent cosmogonic (i.e., solar) Ar/O abundance ratio gives \( [\text{Ar}/\text{O}] = 0.00372 \) (Grevesse & Sauval 1998). Figure 2 presents the derived correspondence between the error-weighted average brightness \( B \) of the two Ar lines and the ratio of the quantity \( Q_\text{Ar}/Q_\text{O} \) to its cosmogonic value.

Although we recognize the difficulty of connecting coma abundances to nuclear abundances with precision, because one does not at present know exactly how gases are stored in the

⁶ The adopted background level that we are using is based on the entire 825–1100 Å MRES spectrum. If we instead adopt an upward-sloping background that better corresponds to a slope set by the three lowest pixel brightnesses in the 950–1100 Å MRES spectrum, then one retrieves 22 R at 1049 Å and 10 R at 1067 Å. Although we do not advocate such a choice of background, we do note that it does more closely reflect the 2.4 : 1 brightness ratio expected on the basis of the g-factors of the two Ar lines.

⁷ On the date of our observations, the projected MRES slit size at the distance of the comet was 57,600 \( \times \) 126,600 km. The Ar photoionization scale length at 0.915 AU (\( 2.7 \times 10^6 \) km) is large compared with the EUVS slit.

⁸ Owing to the fact that we observed Hale-Bopp essentially at perihelion, when its heliocentric radial velocity was consequently small, no Swings effect correction was made.

⁹ As a result, inferring absolute abundance ratios with high confidence will likely remain problematic until cryogenic comet nucleus samples can be returned to Earth.

₁₀ CO is almost as volatile as argon. It is intriguing that Hale-Bopp’s coma is enriched in Ar (this Letter) and also has a notably high CO abundance (Biver et al. 1997).

₁¹ Although near-surface thermal segregation effects, which are difficult to predict accurately at present, could in principle affect the accuracy of this result.
relative to cosmogonic proportions (Krasnopolsky et al. 1997); this is strong evidence that Hale-Bopp’s deep interior has been warmed above 20 K.

Together, the EUVE satellite and EUVS rocket experiment results trap Hale-Bopp’s bulk internal temperature at the point of having exceeded the Ne sublimation loss range of 16–20 K but not the Ar sublimation range of approximately 35–40 K. These temperature constraints are consistent with others retrieved for Hale-Bopp from H2O ortho-para ratio (Crovisier et al. 1997) and D/H ratios (Blake et al. 1999). We interpret our result as indicating either that the solar nebula was far colder and far richer in Ar than models typically predict (Lunine, Owen, & Brown 2000) or that Hale-Bopp was formed in the cold Kuiper Belt region (i.e., well beyond the 20–30 AU Uranus-Neptune zone) and was then subsequently ejected to the Oort Cloud (its more recent dynamical home) without ever spending much time in the (warmer) Jupiter-Saturn zone, or both. Although either implication is contrary to “conventional wisdom,” we note that the transport of comets from the Kuiper Belt region (usually after Neptune-induced inward evolution) to the Oort Cloud has been detected in recent dynamical simulations of Oort Cloud formation (Dones et al. 2000).

This first detection of a native cometary noble gas (argon) whets our appetite for more measurements with which to assess how typical Hale-Bopp is in its Ar abundance. We also look forward to the detection of other noble gases in comets, particularly Ne and Kr, and to the eventual determination of whether or not the ices within individual comets contain varying proportions of Ar and other chemically inert tracers, as a guide to understanding the heterogeneity versus homogeneity of material within cometary nuclei and therefore better still understanding their origins.

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