**THE CHEMICAL AND PHYSICAL PROPERTIES OF COMETS:
UNIFORM ANALYSES OF 32 YEARS OF NARROWBAND PHOTOMETRY**

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THE CHEMICAL AND PHYSICAL PROPERTIES OF COMETS: UNIFORM ANALYSES OF 32 YEARS OF NARROWBAND PHOTOMETRY

INTRODUCTION AND OVERVIEW

In this proposal, we request continued NASA support for the systematic analysis of narrowband photometric observations of cometary comae obtained during the previous 32 years. In 2005 we initiated this investigation of our entire database – now 150 comets observed on over 770 nights – incorporating improved filter calibrations which effectively decontaminate the ultraviolet continuum filter of C3 emission, resulting in greatly improved NH flux measurements and associated ammonia abundances, and for the first time yielding meaningful colors of the dust grains. Based on measurements of cometary comae, our on-going uniform taxonomic and dust analyses for the database as a whole will tightly constrain the chemical and physical properties of comet nuclei and the dust grains released from these nuclei. Each of these properties will be examined for correlations with age, evolution, and site of the comet's origin. The results of these investigations, particularly from the improved ammonia measurements, will also permit us to examine several additional compositional groupings hinted at in our original analyses (A'Hearn et al. 1995), and will place additional strong constraints on the conditions present and the processes which took place during comet formation in the outer proto-solar nebula. Differences in the chemical composition or physical attributes among comets can indicate either differences in primordial conditions or evolutionary effects. Many comets exhibit significant seasonal variations in gas and dust production rates, and a sub-set show variations in coma composition with season, implying probable compositional inhomogeneities across their surfaces. The actual cause of a specific difference in properties can be determined by statistical analyses of the chemical, physical, and orbital properties of a large number of objects. Representing the single largest dataset within the database since Halley, we also propose to perform a complete and detailed analysis of our Hale-Bopp photometry, which will yield dust and gas production rates as a function of distance and season, and determine to what degree compositional inhomogeneities exist among the source regions on the nucleus. We will also perform detailed comparisons of our water production rates for comets also measured in Crovisier's (200??) radio database, to investigate the possible systematic effects associated with the two observational methods.

Programmatic Notes

A program of on–going cometary research exists at Lowell Observatory by the PI and associates. Current grants include PAST funding for on-going coma compositional studies and for coma imaging and morphology modeling. In late 2005 we also began the systematic reanalysis of our entire comet photometry database, the predecessor to this proposal. In addition to the PI and Co-I, a part-time research assistant (currently A. Bair, a former N. Ariz. U. student with a Masters degree) is working on the database reductions. The level of support requested here for the acquisition and analysis of new narrowband imaging of comets is equivalent to 45% of one full-time scientist (33% of the PI and 12% of the Co-I), along with 33% of a research assistant.

SCIENTIFIC JUSTIFICATION AND PREVIOUS AND CURRENT WORK

Scientific Justification

Primary objectives of much of comet research are to achieve an understanding of the origin, basic physical characteristics, and fate of cometary nuclei. While not wholly immune from evolutionary processes while "stored" in the Oort Cloud or Kuiper Belt (cf. Stern 1990), comet nuclei are less processed than any other currently accessible class of objects available for detailed study today. Therefore, knowledge of the bulk chemical composition of comets and how the composition varies among individuals or with evolution due to solar radiation can provide strong constraints on the composition and temperature of the outer protoplanetary nebula at the time solid bodies began to form 4.5-4.6 billion years ago (cf. Mumma, Weissman, and Stern 1993). It is also now acknowledged that a significant fraction, if not the majority of Earth's (and Mars') inventory of water was delivered by comets during the era of heavy bombardment, and that comets and asteroids are the cause of at least some of the mass extinction events in Earth's past. Therefore, the proposed investigations of comets clearly fall under NASA's Strategic Sub-goal 3B to "Advance scientific knowledge of the origin and history of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space." In particular, improved understanding of the original physical and chemical properties of comets and how these properties evolve over time directly address objectives regarding the processes that determine the origins and characteristics of bodies in our solar system, the nature and history of volatiles and organic compounds, and the sources of simple chemicals that contribute to prebiotic evolution and the emergence of life on Earth. As stated within NASA's Strategic Goals (Sub-Goal 3C): Comet particles "are likely to provide clues about the nature of the solar systems's building blocks." The planned research also provides support towards NASA's priorities for robotic solar system exploration beyond 2016 which include a goal of returning samples from the surface of a comet (2006 NASA Strategic Plan, pg 40); because most short-period comets only have apparitions with good viewing circumstances every 2nd or 3rd apparition, in many cases the comet does not have a good apparition in the interval following its selection as a target but prior to the encounter. Therefore, our photometric studies have emphasized detailed investigations of likely target comets when they are well-positioned in the assumption that one or more of them will become actual future mission targets. Additionally, the proposed research directly addresses specific objectives of the Planetary Atmospheres program, including the improved understanding of the origins, evolution, and composition of planetary atmospheres, including comets. Moreover, our database contains observations of every comet that has been targeted for a spacecraft mission, and thereby provides a valuable bridge between detailed mission results from selected targets to the much broader context of where each individual comet fits among the whole.

As described in more detail later, the first evidence of compositional variations due to place of origin was presented by A'Hearn *et al.* (1995) from our first systematic examination of the chemical composition of comets, using the observations we obtained during the first 17 years of our narrowband photometry program. In brief, nearly all comets believed to have arrived following storage in the Oort Cloud have a similar composition, which we called "typical", but only one-half of Jupiter-family comets (short-period comets believed to have formed in the Kuiper Belt) had this same composition while the other half exhibited varying depletions of carbon-chain molecules. Because no evolutionary trends in composition were evident, although other effects due to aging were discovered, we concluded that the variation in composition implied differences in the conditions present at comet formation, with the threshold between the typical and depleted classes located within the Kuiper Belt. Since our study, it has become evident that the Kuiper Belt is composed of three dynamical sub-classes – Classical, Plutinos, and Scattered Disk – and perhaps only the Scattered Disk population is a significant source of Jupiter-family comets.

Numerous studies during the past two decades have also revealed a physical picture far different from that expected on the basis of the classical dirty snowball model. Although indisputably icy, comet nuclei have been found to be exceedingly dark and spectrally distinct from asteroids. They are irregular in shape with activity confined, in many cases, to very restricted regions of their surface. We also unexpectedly found a very strong correlation between the measured dust-to-gas ratio and the perihelion distance of the object, where the variation with perihelion distance among different comets is much larger than the variation exhibited by individual objects as they approached or receded from the Sun. This correlation likely implies a physical change in the surface properties of nuclei due to solar heating, altering the number of optically important grains released from the nucleus when normalized by the amount of ice which is vaporized. (Note that for nominal particle size distributions, grains between about 0.5-5 microns contribute most of the reflected light detected in the visible regime.) It is unknown whether the correlation with perihelion distance is due to a change in the size distribution of grains (some dust-poor comets, such as 2P/Encke, have significant populations of very large-sized grains), or simply due to an overall decrease in the number of grains. Measurements of the color of dust grains for a large sample of objects should resolve this issue, since dust color is primarily associated with the particle size(s) (cf. Kolokolova *et al.* 1997).

Techniques and Systematic Studies

As already noted, comets are the most pristine remnants from the time of solar system formation, and so their chemical composition provides important clues to understanding the conditions present in the early solar nebula. However, until comet nuclei can be sampled directly, compositional studies are restricted to analyses of cometary comae. The comae of a few comets have now been measured during spacecraft flybys, providing invaluable data not obtainable by other means, and a small sample of dust grains from the coma of Comet Wild 2 are now undergoing detailed examinations in laboratories after having been brought back by the successful Stardust mission. But placing these data sets into a much broader context neccessarily requires large numbers of comets to be sampled. While the largest compositional studies are those based in the visible regime, none of the molecular species observable in the visible region of a comet's spectrum originate directly from the nucleus. Rather, those species detectable in the visible are daughters or granddaughters resulting from photodissociation of more complex parent molecules. The spectroscopic features produced by native nucleus species mostly occur in the IR and mm regimes. With major improvements in instrumentation in the past decade, systematic studies of parent species are increasingly being undertaken by several research groups, but so far these studies typically consist of only about 1-2 dozen objects and have generally included few Jupiter-family comets (believed to have originated from the Kuiper Belt), simply because these objects are seldom sufficiently bright. We remain hopeful that IR and mm observations obtained during the next decade will result in greatly improved statistics and permit detailed intercomparisons with visible studies.

Several long-duration survey programs to study composition in the visible regime have been conducted and results published. (A sample of more than 50 comets was observed in the UV by the IUE satellite, but a homogeneous study of composition from these data has not yet been published.) Except for our own program of narrowband photometry using a conventional photoelectric photometer, each of these surveys has employed the spectrophotometric technique. As usual, there are pros and cons with each technique, and we consider the two methodologies as complementary: Spectroscopic methods permit the direct detection of the shape of an emission feature, simplifying the task of subtracting the underlying continuum, and permitting the measurement of weak features such as CH, NH_2, or [O I]. However, even long-slit spectrographs only sample a very small fraction of the total coma, and a single slit orientation may not adequately describe asymmetries in the coma. In comparison, narrowband aperture photometry usually samples a larger portion of the coma, and so less extrapolation to total abundances is required and derived quantities such as production rates are less model dependent. Due to the steeper radial fall-off of dust with distance from the nucleus as compared to the gas daughter species, there is also proportionally much less continuum to be subtracted from the emission bands, permitting the clear detection of emission even in comets having high dust-to-gas ratios or very low surface brightness. Aperture photometry is also appropriate for large survey programs because of the simplicity and stability of the instrumentation, relative ease of data reduction, and the adequacy of modest-sized telescopes. However, only the stronger emission bands can be dependably isolated with filters, and so our compositional studies are limited to five molecular species: OH, CN, C_2, C_3, and NH. Results from our program will be presented in the next section, after first briefly summarizing a few of the many findings obtained from the spectroscopic programs.

The first spectroscopic survey results were published in a series of papers by Newburn and Spinrad (1984, 1985, 1989) containing production rates for CN, C_2, C_3, water (based on O [^{1}D] emission), and dust for 25 comets. Production rates for CN, C_2, C_3, and dust were published in several subsets of the McDonald Observatory survey of more than 80 comets headed by A. Cochran and her colleagues (Cochran 1987; Cochran *et al.* 1989; Cochran 1990; Cochran *et al.* 1992; Storrs *et al.* 1992). Both of these surveys concluded that, other than for a few exceptions for which C_2 and C_3 were depleted, all comets exhibit essentially the same abundance ratios, but that the dust-to-gas ratio varies widely. Newburn and Spinrad also concluded that CN abundance exhibits a strong correlation with dust, and that CN probably has both a dust as well as a gas source. More recently, Fink and Hicks (1996) summarized their results for 39 comets, 21 of which showed detectable emission from CN, C_2, NH_2, and O [^{1}D]. They identify three comets having unusual compositions, along with a smaller dispersion of abundance ratios among the other 18 objects.

The Lowell Photometry Program: History and Original Database Results

The Lowell narrowband comet photometry program was begun by A'Hearn and Millis in 1976 with a primary objective of establishing the group properties of comets and the degree to which individual comets varied from the ensemble. That is to say, we have sought to determine the range in composition, intrinsic activity level, rate of response to changing insolation, etc., displayed by these small icy bodies. Results for CN, C_2, C_3, and the continuum for a dozen objects were reported by A'Hearn and Millis (1980); at this same time filters isolating emission bands of OH (3085 Å) and NH (3350 Å) were added. The International Halley Watch (IHW) filter set was phased in during 1983/84, and these filters were used until 1997, at which time we transitioned to our current filter set (described later). A second summary of results was published by Osip *et al.* (1992) for nine possible spacecraft targets (5 of which have been or currently are targets of actual missions), while individual detailed results for over a dozen additional comets have also been published.

In collaboration with R. Millis, M. A'Hearn, and P. Birch, the PI and D. Osip began the systematic rereduction of all data in hand in 1990, and at the end of 1992 we "froze" the database with a total of 2020 sets of observations for 85 comets measured over the course of 444 nights. Using a self-consistent model and model parameters (see later section), absolute molecular production rates and relative abundances were computed, permitting investigations of chemical compositions as a function of heliocentric distance and from one comet to another, the effective active area required to produce the observed water and a corresponding lower limit to the size of the nucleus, and the correlation or lack thereof of any measured properties with age or origin. The results from these investigations were published by A'Hearn *et al.* (1995), and some of these are described next.

Several of our results appear to be associated with a comet's evolution or dynamical age. These include the previously mentioned strong correlation of a comet's measured dust-to-gas ratio with perihelion distance. Jupiter-family comets generally have steeper heliocentric distance-dependencies, greater asymmetries about perihelion, and smaller fractions of their surfaces still active than do other comets. Surprisingly, of 20 comets having nucleus size measurements, 14 had fractional active areas of less than 3% based on our water measurements, a water vaporization model, and the total surface area of the nucleus, i.e. nearly the entire surface was crusted over or otherwise inert. However, while the statistics are quite poor, there was no convincing evidence of a change in production rates from one orbit to the next for short-period comets, except for objects which had undergone a perturbation of their orbit, implying source regions are generally long-lived. Except for dynamically new objects, comets which exhibit asymmetries in gas production around perihelion do so in near-equal numbers with the peak occuring before or after perihelion, directly implying that the cause of asymmetries is not due to thermal lags, but is likely seasonal in nature. A strong correlation of dust production with CN production was observed, similar to that detected by Newburn and Spinrad (1989), possibly implying that for many comets much of the CN and some of the C_2 is produced from grains in the coma rather than from nuclear ices.

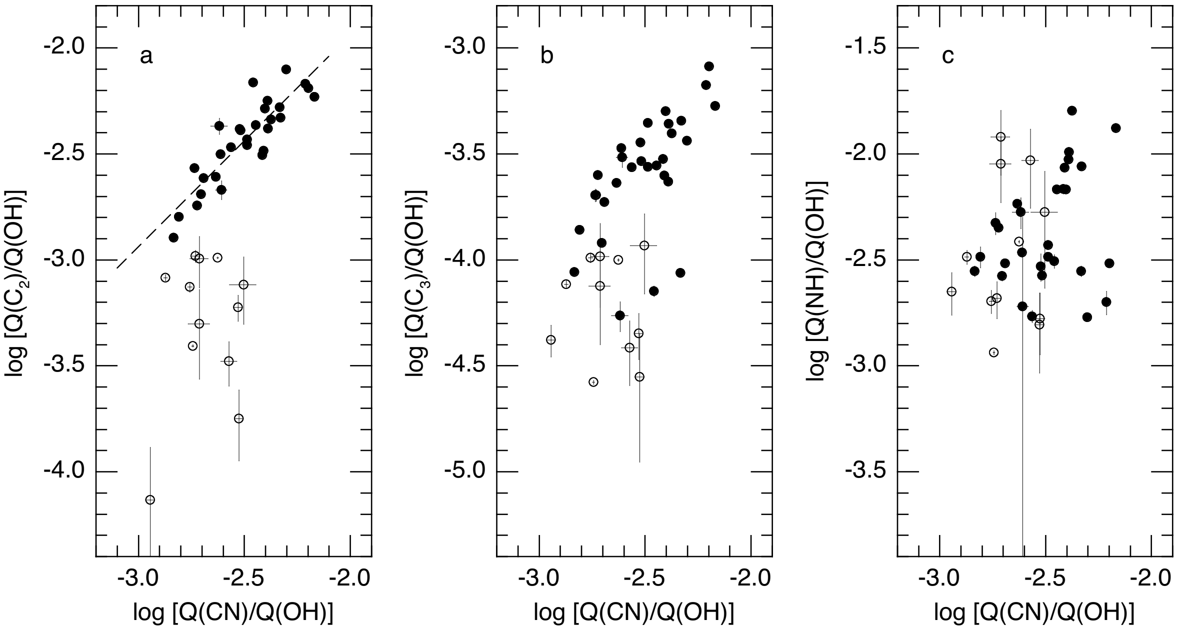

Figure 1. a) Two taxonomic groups are identified based on the relative production rates of OH, CN, and C_2 for the 41 comets contained within our restricted database. Note that within the "typical" group (filled symbols), CN and C_2 vary together with respect to OH (the line has a slope of unity). b) The pattern for C_3 is similar to that for C_2 but with more scatter. c) NH exhibits no discernible pattern, probably due inadequacies in the continuum removal caused by C_3 contamination of the UV continuum filter. [From A'Hearn *et al.* 1995]

A taxonomic analysis was performed on a subset of the database for which measurements were made of all 5 gas species (OH, CN, C_2, C_3, and NH), and where each comet had been observed sufficiently (two or more nights of observations; three or more sets of data) to verify the quality of the data. These constraints resulted in a restricted database consisting of 41 comets, including 18 Jupiter-family objects. In agreement with results of previous studies (Newburn and Spinrad 1984; 1989; Cochran 1987), these data confirm that, in general, comets display a remarkable overall homogeneity in gas abundance ratios, but that the gas-to-dust ratio varies by over 2 orders of magnitude. However, based on the various gas species' abundance ratios, including those of OH and NH which were not measured in other studies, our analysis identified 2 primary taxonomic groupings (see Figure 1), and evidence of as many as 8 secondary groupings. In the first primary group (about 70% of the sample) comets have the same basic, i.e., "typical," composition. However, a distinct trend is observed even within this "typical" group: while the abundance ratio of each minor gas species with respect to OH can vary by as much as a factor of 3-4 from the mean value, the three carbon-bearing molecules (C_2, C_3, and CN) all vary together through this "normal" or "typical" range. Fink and Hicks (1996) report a similar trend for CN and C_2 as compared to water, the latter based on forbidden O measurements. Comets in our second taxonomic group exhibit significant depletions in the pure carbon species (C_2 and C_3) – by as much as a factor of 20 from the mean value for the typical group – but CN remains in the same range with respect to OH as with comets in the "typical" group. Because we did not see any evidence of a trend in composition with an individual comet's distance from the Sun, we were able to rule out artifacts due to our choice of model parameters. There was also no evidence of trends in composition with dynamical age for long-period and Halley-family comets, nor with fractional active surface area for Jupiter-family comets, and so we ruled out evolutionary causes. (Indeed, the comet believed to have had the most thermal processing and therefore to be the most evolved, 2P/Encke, has a typical composition with no sign of carbon–chain depletions.) Instead, these results most likely imply that a non-negligible fraction

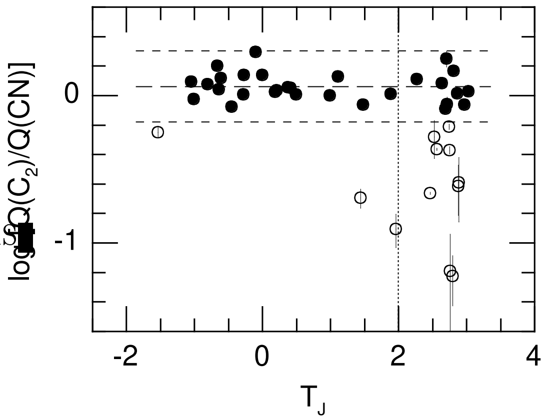

Figure 2. Production rate ratio of C_2 to CN as a function of the Tisserand invariant for Jupiter, T_J. Comets having "typical" composition are those within the horizontal band, while carbon–chain depleted comets lie below this band. One–half of Jupiter–family comets ($T_J > 2$) are depleted, while only two non–Jupiter–family comets ($T_J < 2$) display significant depletions, and one of these – P/IRAS – oscillates across the T_J=2 boundary over time. Statistically, most Jupiter–family comets should have originated in the Kuiper Belt, while most other comets are believed to have come from the Oort Cloud. [From A'Hearn *et al.* 1995]

of comets (or their constituent components) formed at a different temperature and, therefore, a different location and/or time than did the majority of comets in our database. More importantly, these 2 compositional groups are strongly correlated with orbital elements, with nearly all Halley–family and long period comets having typical chemical composition while approximately one–half of the Jupiter–family comets are carbon–chain depleted (see Figure 2). This constitutes the first evidence of compositional differences related to origin, as the majority of Jupiter–family comets are believed to originate from the Kuiper Belt while most non–Jupiter–family comets come from the Oort Cloud.

By employing formal statistical techniques, including principal component analysis and cluster analysis, we were able to detect evidence of several additional compositional sub-groupings. In all, as many as 8 associations were noted and identified from the restricted database of 41 comets, with the the relative abundance of NH apparently a major discriminator among some of the groups. However, the contamination of the UV continuum filter by the long wing of the C_3 emission band resulted in a contaminated continuum value being subtracted from the relatively weak NH emission, thereby yielding very uncertain NH values. Even so, it was evident that the three most strongly carbon-chain depleted comets are also among the comets with the lowest NH abundances. This same contamination of the UV continuum filter also prevented A'Hearn et al. from investigating the color of the dust grains; however, as discussed in the next section, we now have developed a procedure which can use the measured C_3 flux to determine the amount of contamination present in the UV filter and correct for it.

Finally, we note that while little or no variation in composition is measured in individual objects as they approach or recede from the Sun, changes in abundance ratios are evident in some comets when pre-/post-perihelion observations are compared. Such pre/post variations are believed to be related to seasonal effects, with different source regions (with differing compositions) moving into or out of sunlight; the high obliquity of a comet's rotation axis can result in a source region's rapid change from "winter" to "summer" (or vice versa) during its perihelion passage. Comet Encke is one example of presumed compositional inhomogeneities among source regions, as the water production is nearly symmetric about perihelion, while the minor species display asymmetries before and after perihelion by factors of 3-4 (A'Hearn *et al.* 1985). Other evidence for chemical inhomogeneities across a comet's surface include variations in the relative abundance of formaldehyde with respect to other species as a function of rotation in Halley (Mumma *et al.* 1993), variations in the relative abundances of HCN and CS with rotation in Hale-Bopp (Woodney 2000), and the case of Wild 2 which we discuss in the next section.

The Lowell Photometry Program Since the Original Database Study

Following the publication of our 85-comet database results (which to date is the most cited ground-

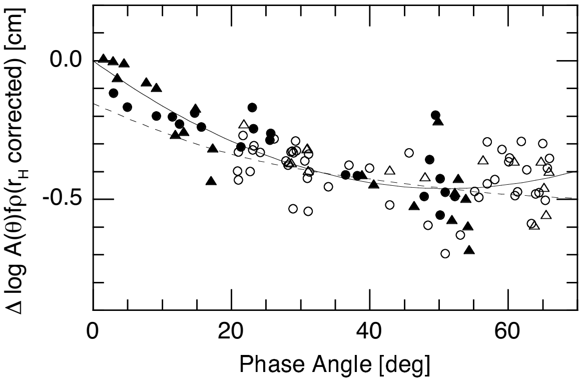

Figure 3. Phase angle dependence of dust for Comet 1P/Halley. This figure shows the log of A(θ)fρ plotted against the phase angle after removal of the trends with heliocentric distance. (Multiply the ordinate axis values by -2.5 to obtain units of magnitudes.) The curvature of the phase dependence is clearly evident (solid curve is a 2nd-order fit), and is significantly steeper than the phase function by Devine (1981; dashed curve). We plan to combine the Halley curve between 0° and about 40° with other curves available for larger phase angles to correct database dust values for phase effects. [From Schleicher, Millis, and Birch 1998]

based observational comet publication), we were able to complete a detailed analysis of Comet Halley's photometric properties as a function of heliocentric distance, season, and solar phase angle (Schleicher, Millis, and Birch 1998), and place Halley into the broader context of the database. A particularly useful result was that we were able to determine the phase effect of dust from 1.5 to 66 degrees for a single comet. This phase function for Halley's dust grains shows pronounced curvature over the observed range of phase angles (see Figure 3), with a slope of 0.045 mag/degree near 0° and nearly flat at angles greater than about 30°. The peak of the phase function at 0° is 2.9 times that at the minimum near 50°, compared with the 2× enhancement typically measured for the zodiacal light. Consistent with determinations by several other investigators over shorter intervals of phase angle (cf. Millis, A'Hearn, and Thompson 1982; Meech and Jewitt 1987), we believe that the Halley phase function represents the most credible published phase curve to very small phase angles for any single comet. Combining our phase function with either that for Comet West or for Comet Bradfield (1980 XV) by Ney and Merrill (1976) and by Ney (1982), respectively – each extending from about 30 to 150° – would arguably yield the most complete representation of the phase curve of cometary dust available today. Our on-going reanalysis of our entire photometry database will use this composite phase function to remove artifacts in computed dust production, such as we recently observed for Comet LINEAR (2000 WM1) (Schleicher, Woodney, and Birch 2002) when it rapidly passed through small phase angles.

Due to a degradation in many of the IHW filter sets, coupled with the arrival of Comets Hyakutake and Hale-Bopp, NASA agreed to support the production and calibration of new sets of narrowband filters in time for Hale-Bopp's perihelion passage. This effort was headed by the PI and Co-I Farnham, with assistance from Collaborator A'Hearn. As a part of the calibration process, a new methodology was developed for the removal of emission band wings from unavoidably contaminated continuum bands in the UV and green regions of the spectrum, along with an improved non-linear extinction model for the OH band at 3090 Å. In particular, the new iterative decontamination technique (see Farnham *et al.* 2000) uses the measured fluxes in the continuum bands to remove underlying continuum from the C_3 and C_2 filter fluxes, which can then be used to compute the amount of contaminating emission in the continuum filters. At each step of the iteration the remaining contamination is reduced, until essentially pure emission fluxes and continuum fluxes are obtained. We next completed the determination of revised filter coefficients for the original Lowell filter set and the IHW filter sets using this new decontamination methodology, and the details are contained in an appendix of our Wild 2 paper (Farnham and Schleicher 2005). By decontaminating the UV continuum measurements, for the first time we now have the ability to examine the color of the dust coma for nearly our entire database (no UV continuum filter was used prior to 1980). As described below, significant differences have already been observed between Comets Hyakutake

(1996 B2) and P/Borrelly in the characteristics and variations of the color of dust grains with heliocentric distance.

During the past several years, we have conducted a series of observing campaigns (under Planetary Astronomy funding) of interesting targets, to investigate production rates as a function of distance, to search for seasonal effects, and, in the cases of the short-period comets (all of which have been observed at previous apparitions), search for possible evolutionary variations from orbit to orbit. A few of the results most relevent to the proposed investigation follow:

Comet Hyakutake (1996 B2) was the first comet for which we rereduced photometric measurements obtained with the IHW filter set with our new procedures to remove the contamination of the UV continuum filter by the wing of the C_3 band. Some of the results (see Schleicher and Osip 2002) included a very shallow heliocentric distance (r) dependence of water, and active areas encompassing about 25% of the nucleus surface. Our solution for the pole orientation and location of two active sources (based on modeling of CCD images of dust jets) eliminates the possibility that seasonal effects caused the shallow r-dependence, and instead imply that it must be due to a decreasing proportion of icy grains. We also found that, throughout the apparition, Hyakutake's continuum is generally redder in color below 5000 Å than at longer wavelengths; however, the dust color progressively changes from being significantly reddened at large heliocentric distances (r) to near-solar at small r. This change of color with distance directly implies a significant change in grain sizes or a changing proportion between two or more grain populations.

We conducted a major observing campaign of Comet 19P/Borrelly, the target of the Deep Space 1 spacecraft, during its 2001/02 apparition. In addition to imaging the sunward jet throughout the apparition, photometric data were obtained to extend the orbital coverage as compared to our measurements from three previous apparitions, and to place the Deep Space 1 spacecraft encounter measurements into this broader context. Results published by Schleicher, Woodney, and Millis (2003) include water and dust production rates only 3 days prior to the DS1 encounter, and confirmation of a steep post-perihelion decrease in the water (and other gas species) production rate measured during previous apparitions – the rate dropped by about 25x between 1.36 and 1.89 AU, nearly a factor of 10 greater decrease than would be expected from a simple water vaporization model. The solution for the orientation of the rotation axis and the jet's source location (based on our imaging of Borrelly's jet) and size (based on the width of the jet and the absolute water production) directly predicts a strong seasonal effect as the source region moves from summer to winter following perihelion, *quantitatively* reproducing the extremely steep dependence with heliocentric distance (r). In other words, these observations confirm that the steep r-dependences are induced by seasonal changes in the illumination of a heterogeneous surface, rather than caused by the exhaustion of volatiles. Moreover, the vaporization rate is simply determined by the cosine of the sun angle, rather than requiring the sun to be high overhead to illuminate deep vents. The dust is strongly reddened throughout the apparition.

We (Farnham and Schleicher 2005) completed the analysis of multi-apparition observations of Comet 81P/Wild 2, the target of the January 2004 encounter by the Stardust spacecraft which has now returned to Earth a sample of cometary dust grains. Perhaps our most significant results are that OH, NH, and the dust all show pronounced asymmetries about perihelion, with peak production rates occuring approximately 80 days prior to perihelion. In sharp contrast, little or no asymmetry is detected for the carbon-bearing compounds, CN, C_2, and C_3. Combined, these characteristics imply strong seasonal effects, requiring localized active regions and significant chemical compositional inhomogeneities across the surface. These conclusions are similar to those obtained by A'Hearn *et al.* (1985) for Comet 2P/Encke, although in Encke's case, it was the minor species exhibiting a strong asymmetry while the OH showed almost no asymmetry.

Analyses of photometry of two other spacecraft targets have also been completed recently: The first was for new Rosetta target 67P/Churyumov-Gerasimenko, where another strong production rate asymmetry is observed, but with the opposite sense of that exhibited by Borrelly; Comet C-G also exhibits a small depletion of carbon-chain molecules (Schleicher 2006). The second was for the literal Deep Impact target 9P/Tempel 1, for which the PI intercompared measurements from three apparitions to unexpectedly determine a large and progressive secular decrease in production rates since 1983, but by differing amounts for different species, with water decreasing the most (by 58%) and dust the least (by 23%). Strong seasonal effects are also observed, and the time of peak production also varies by species (Schleicher 2007a).

Finally, two recent comets – 73P/Schwassmann-Wachmann 3 and 96P/Machholz 1 – have provided important new results regarding compositional taxonomy and the cause of compositional variations. The partial fragmentation of Comet S-W 3 permitted the rare opportunity to probe the interior composition of a comet nucleus. In 2006 we measured the relative composition of the comae produced by the primary body (C) and each of three fragments (B, G, and R). Abundances of carbon-chain molecules yield a classification of strongly "depleted" in the A'Hearn et al. (1995) database, with the Q(C_2)-to-Q(CN) ratio depleted by factors of between 7 and 8 for components C, B, and G, and a comparable upper limit for component R. With the material released from the interior of S-W 3 yielding comparable depletions of carbon-chain molecules as with the original surface of the nucleus (from observations by Fink and Hicks 1996 taken in 1990), we can conclusively state that carbon-chain depletion is *not* caused by evolution of the surface, and so must instead reflect the primordial composition at the time and location that the comet accreted (Schleicher et al. 2006). This past month, the PI discovered that the composition of short-period comet Machholz 1 is near-unique, having a CN abundance ratio to water depleted by 200x, while C_2 and C_3 are somewhat depleted but NH (and therefore ammonia) is at the high end of the normal range (Schleicher 2007b). It is as yet unclear if this extremely low CN-to-OH ratio for Machholz 1 puts it in the same compositional class with Comet Yanaka (1988r) which was strongly depleted in CN and C_2 but not NH_2 (Fink 1992), or represents a new compositional class of comets, since Yanaka had a much greater depletion of C_2 than does Machholz 1. In either case, such extreme values, coupled with our other results, implies that these comets very likely formed in a source region that had significantly different conditions and a low probability of being perturbed into the inner solar system.

THE NEW LOWELL COMET DATABASE INVESTIGATION

History, Methodology, and Current Status

As just described, under PAST funding we have conducted a series of observing campaigns of comets of particular interest. While at the telescope for these campaigns, we also routinely obtain observations of other accessible comets. Thus, our photometric database has continued to grow at a near-steady rate even though our scheduled observing is driven by a much smaller number of specific targets. In the case of multi-apparition short-period comets, new observations have focused on extending the observational arcs to improve the statistics for studies of pre/post-perihelion asymmetries; to further investigate possible effects due to aging, such as a depletion of volatiles over several orbits; and to reduce the uncertainties on the mean abundance ratios used in the taxonomic analyses. With the experience of having performed the original full database analysis, we were also better aware of just which source of uncertainty tended to dominate the final average values, and so we were able to adjust our observing strategies accordingly. Thus, the new data are generally of better quality than those obtained in the early years of our program. Moreover, most new comets observed since the original database analysis were measured on two or more nights with a total of three or more data points, i.e. fulfilling our requirement for including a particular object into the restricted database used in the taxonomic analyses. We have, therefore, now more than doubled both the original taxonomic sample size of 41 comets (to nearly 90) and the number of Jupiter-family comets within the restricted set.

With a much larger database – currently 150 comets observed on more than 770 nights – and our new abilities to effectively remove the contamination by C_3 emission in the UV continuum filter – yielding both dust colors and greatly improved NH production rates – we proposed (successfully) to the Planetary Atmospheres Program in 2004 to initiate a new database investigation. Our first and most time consuming goal in this investigation was to reduce or rereduce all comet narrowband photometry obtained since 1976 in a uniform manner, applying the new continuum decontamination methodology developed for the HB filter sets and back-applied to each of the older filter sets,

To begin, the PI updated several parts of his reduction software to make it easier for the user (himself or his assistant, Allison Bair) to identify and fix common problems associated with less-than-perfect observational sets, such as when clouds prevented a full set of extinction stars or standard stars to be measured. Due to the anticipated retirement of our long-time collaborator Peter Birch (Perth Observatory), we next concentrated on the 200+ nights of observations he has contributed to our narrowband photometry program. First, we reduced or re-reduced nearly 160 nights of data which he supplied prior to 2005. Of these data, about 1/4 had various issues regarding the circumstances on the individual nights or the quality of the data. The PI then traveled to Perth Observatory to work directly with Birch for a 3-week interval, examining log books and, in the case of two dozen nights, located the raw data for which only reduced results had previously been available. During this "search and rescue" process, we also located another 25 nights of data not previously known to the PI. In total, we located and reduced 211 nights of Perth photometry, 9 of which have to be removed from the database due to various problems.

We next located the raw data for all but a few dozen nights of Lowell observations. The missing observations were all taken in the first few years of the database, and if these raw data continue to remain elusive, we will use the existing partially reduced data as our starting point for the new reductions. All data taken since the original database paper, i.e. 1993 and later, have now been reduced to the point of finalizing the best extinction coefficients and absolute flux zero points based on standard star measurements. Having already been reduced once in a uniform manner for the original database, the primary remaining task for the data obtained prior to 1993 is the determination of the effective atmospheric ozone which affects extinction in the ultraviolet OH filter. We expect this final calibration step to be completed by the 2nd anniversary of this grant.

We have also begun the 2nd phase of the data reduction: reducing the comet measurements to gas production rates and dust $A f \rho$ values, and determining which of the data points previously identified as being of questionable quality (due to observer log entries or evidence from standard stars) are in fact viable. This requires the detailed intercomparison of comet results within an observing run and/or within an entire apparition of each comet. All observations from Perth Observatory have already been processed in this manner, as have the 1993 and later Lowell data, and we expect to complete this processing for the older Lowell data this fall. As the quality of each dataset is ascertained, we also examine the observations for trends that might be artifacts of inappropriate model parameters. Note that, following the derivation of continuum fluxes and emission band fluxes, we calculate the number of gas molecules within the photometer aperture that were required to produce the measured gas flux for each species by the standard application of the appropriate fluorescence efficiency or g-factor (cf. A'Hearn et al. 1995). We then extrapolate the number of molecules in the aperture to a whole coma abundance by application of a standard Haser model, and it is at this stage where the results are most model dependent.

Various models are available, but we usually use the Haser model due to its simplicity and because we have determined Haser scalelengths for each of our gas species which successfully reproduce the observed radial profiles under most circumstances (cf. Randall *et al.* 1992; A'Hearn *et al.* 1995). The primary exception was for Comet Hale-Bopp near perihelion when the nominal Haser scalelengths must be increased by 2-3x to remove trends with aperture size due to the combination of unusually large gas outflow velocities in this very high production comet coupled with low solar activity (Schleicher *et al.* 1999; Rauer *et al.* 2002). We will, therefore, examine our datasets for any evidence of systematic trends in the derived production rates with photometer entrance aperture size.

Once a total coma abundance is computed, this quantity can be divided by the lifetime of the species (usually controlled by the photodissociation rate from solar radiation) to compute the production rate of the species, Q, i.e. the rate at which new molecules (or their parents) must be released from the nucleus to maintain the observed abundance. Thus far we have used constant values for the lifetime of each species, but because the lifetime of species can vary by as much as a factor of 2 with solar activity, we hope to be able to locate appropriate activity-dependent values to be applied when computing final production rates. For the single case where the parentage of the observed species is unambiguously known – H_2O is the sole parent of OH – we compute parent production rates. Knowledge of the water production rate is particularly important because water is the dominant volatile constituent of comets.

Finally, we note that the non–physical nature of the Haser model is often used to claim that "real" production rates cannot be obtained, and a more physical model such as the vectorial model or Monte Carlo model must, instead, be used in the analysis process. While certainly true when modeling time-variable phenomena, this is not the case when computing the production rate of an observed species in near–static equilibrium. In fact, Combi and Delsemme (1980) showed that Haser scalelengths exist which can reproduce any 2-generation Monte Carlo or vectorial spatial profile. We use the Haser model only to extrapolate to a total coma abundance, and then divide by the daughter lifetime to get an absolute production rate. We emphasize that *scalelengths which accurately reproduce spatial radial fall-offs will yield true total coma abundances.* While the daughter lifetime is poorly known for some species, affecting final production rates, this problem equally affects other, more physical models.

To compute an aperture-independent quantity for the dust analogous to gas production rates, we continue to use the formulation first introduced by A'Hearn *et al.* (1984). This quantity, $\mathrm{A}(\theta)\mathrm{f}\rho$, is the product of the bond albedo, A, at a particular phase angle, θ, the filling factor, f, and the projected aperture radius, ρ, as seen on the sky plane. This product will be independent of aperture size if the dust follows a canonical $1/\rho$ spatial distribution for outflowing dust, and will be independent of wavelength if the dust has no color as compared to the Sun. Since no knowledge of the grain properties is required as input to the calculation, the computation of $\mathrm{A}(\theta)\mathrm{f}\rho$ from the measured continuum flux is straightforward, and therefore $\mathrm{A}(\theta)\mathrm{f}\rho$ is often used as a proxy of dust production, somewhat analogous to the gas production rates discussed above. Indeed, the quantity $\mathrm{A}(\theta)\mathrm{f}\rho$ varies proportionally to the dust release rate from the nucleus, but also inversely proportional to the dust outflow velocity. Unfortunately, the very fact that grain properties are not included in $\mathrm{A}(\theta)\mathrm{f}\rho$ means that intercomparisons as a function of time for a single comet or intercomparisons between comets must be made with caution. Particle size distributions are known to differ drastically among comets, and outflow velocities also vary with particle size. Therefore, it can be difficult to determine whether a particular variation or trend of $\mathrm{A}(\theta)\mathrm{f}\rho$ is actually a measure of the rate of release of dust grains from the nucleus, or an indication of changing grain properties. In any case, dust colors will be computed, along with $\mathrm{Af}\rho$ values corrected for phase angle by application of a composite phase curve. Both corrected and uncorrected values will be included in the final database. Somewhat unexpectedly, much greater variation in dust colors, including variations with time, have already been found in several of the comets for which we have performed color analyses, including comets Hyakutake, Borrelly, Wild 2, and Churyumov-Gerasimenko.

Once data are fully reduced, the final production rates and $\mathrm{A}(\theta)\mathrm{f}\rho$ values are imported into our primary analysis package, DataDesk. This commercial software, used in the original database analysis, is specifically designed for exploratory data analysis. With the completion of the reductions of all data obtained since 1993 (i.e. since the original database), we have recently performed a first-look

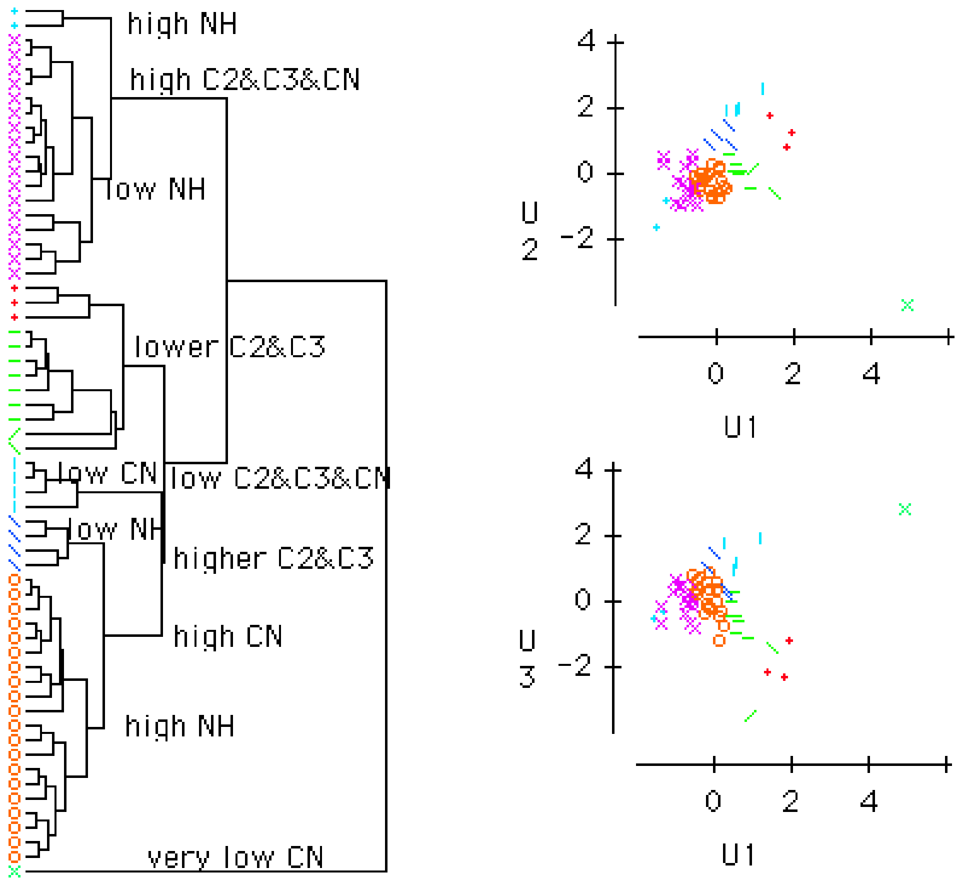

Figure 4. Compositional tree diagram for cluster analysis (left). The 62 comets are linked according to the degree of similarity of chemical composition; the longer the "branch," the more diverse the composition. Newly measured Machholz 1 is the bottom-most branch of the tree. Plots of the first 3 principle components are shown on the right. Symbols are based on major branches from the cluster analysis; the first principle component (U1) consists primarily of near-equal part of CN, C_2, and C_3 with respect to OH, the 2nd p.c. (U2) is dominated by NH with respect to OH, while the 3rd p.c. (U3) consists of near-equal parts of CN and C_2 with respect to OH.

investigation of a compositional taxonomy for these data. In lieu of computing relative abundances by averaging production rate ratios for each comet (a task reserved for after the database is frozen), this first-look simply uses a single, representative data point for each comet. The results are shown in Figure 4, in the form of a dendogram based on a basic cluster analysis for 62 well-determined comets, along with principle component plots based on a separate principle component analysis. Even this first-look confirms several of the sub-groups seen in the original database analysis, and NH abundance is a clear discrimant which often differs from the abundances of the carbon-bearing species (see Figure 4).

PROPOSED RESEARCH

Summary of Proposed Research

As discussed in detail in the previous sections, a large number of findings were made when we performed our original comet photometry database analysis of 85 comets observed through 1992 (A'Hearn et al. 1995). With our new abilities to measure dust colors and derive much improved NH production rates, along with a much larger database as a whole, we proposed and were funded to perform a new set of investigations of our near-homogeneous comet database encompassing 3 decades of cometary comae measurements. We emphasize that these new investigations are not simply an incremental step beyond the original database analysis. Rather, we now have the ability for the first time to determine and examine ammonia abundances for a large number of comets, and determine the relation of ammonia (the grandparent of NH) to carbon and to water. If the threshold between typical and carbon-chain depleted comets is due to the temperature of formation, as suggested by A'Hearn et al., then we would expect the fraction of comets depleted in ammonia to differ from the fraction depleted in carbon-chain molecules. These investigations are also the first time that dust colors (and the associated particle sizes) will be examined for a sufficiently large sample size of comets to examine possible correlations with orbit, origin, and evolution. Consistent with our stated goals for this ongoing research project, we continue to plan on producing 2 papers based on the total database analyses, with one focussing on relative and absolute chemical abundances of the 5 gas species we study, and the other focussing on the properties of the dust grains.

The uniformly rereduced database also greatly facilitates the production of detailed papers focusing on the properties of interesting individual comets or groups of comets. We continue to plan on producing at least 2 focussed papers, in which we will analyze and present all data for a subset of the comets in the database, rather than averaging each comet's data as we do for the taxonomic studies. One subset will be those comets which exhibit strong C_2 depletions, while a likely 2nd subset is a representative sample of long-period and/or dynamically new comets. As originally proposed, we expected to complete 1 of the 2 ensemble papers and 1 of the focussed subset papers during the current grant cycle, and we remain confident these will be completed in 2008. However, also as originally planned, we expect the 2nd ensemble paper, and the second focussed subset paper to require additional effort to complete, which we propose here.

While detailed single-comet investigations were beyond the scope of the original proposal at the requested level of time and effort, here we now propose two such investigations, one each for Comets Hale-Bopp and Tempel 2. Hale-Bopp represents the 2nd largest dataset (after Halley) in our entire database, and a comet for which we were able to measure gas production over the widest range of heliocentric distances due to its inherently large size, while Tempel 2 represents the largest dataset for a Jupiter-family comet which we have not yet conducted a detailed analysis, and exhibits extreme seasonal behavior. Finally, with improved water production rates for our database, we intend to perform a detailed comparision of our water values with those from other investigators, in particular the published database of radio measurements by Crovisier (200???), to explore the possible reasons why there are systematic differences associated with observational technique for some comets but not for others.

Details of Proposed Projects

Dust and Gas Ensemble Investigations: While we expect to continue to add new comet observations obtained under separate funding to our database during the course of this proposed research, for practical purposes we intend to "freeze" the database at the end of 2007, when we will have completed the entire re-reduction process. Bulk analyses will be accomplished in parallel for the gas compositional studies and the dust studies. Average abundance ratios, absolute production rates, and dust colors will be computed at a variety of distances for each comet, so that the behavior of each property can be examined as a function of orbital motion. When possible, phase angle effects will be measured, and adjustments for phase angle will be applied to the dust data based on the measured phase function and/or on our Halley phase function described previously (see Figure 3). Global averages (one per comet for each property) will also be computed, and these averages will be used in subsequent taxonomic classifications using principle component analysis and cluster analysis. All of the resulting properties will also be investigated for correlations with orbital parameters to examine trends with origin and/or dynamical age. In the original analyses the dust-to-gas ratio exhibited a strong correlation with perihelion distance, indicative of physical evolution associated with the amount of heating the surface of a nucleus has experienced. We anticipate a similar correlation for the dust color, as most processes which can alter the amount of dust released from the nucleus would also be expected to alter the size of the released grains.

The results of this compositional analysis, whatever they might be, will give additional strong constraints on the varying conditions within the outer solar nebula. One scenario suggested by A'Hearn et al (1995) hypothesized a temperature gradient within the Kuiper Belt, where the probability to form certain parent species vs. other parents depends upon a threshold temperature. In this case, carbon-chain depleted comets are not depleted in carbon per se, but below a certain temperature the carbon is tied up into other molecules which do not eventually dissociate to produce C_2 or C_3. Knowledge of the parentage of these carbon-chain molecules is lacking, preventing a quantitative constraint on nebula models. In the case of NH, it is generally believed that nearly all of the observed NH is produced either directly or in two steps from ammonia. With a known parent/grandparent, we can reasonably expect that NH taxonomic results will ultimately yield significant constraints on outer solar nebula models.

Until we perform the bulk analyses (in early 2008), we can not be sure whether the dust or the gas investigation will be closest to completion. Once this is determined, we will concentrate our efforts to complete said ensemble paper under current funding, while the second ensemble investigation will be completed during the first year of this new proposal.

Targeted Sub-set Investigations: As previously indicated, we plan at least two additional papers in which all individual data sets for each comet within a distinct group of comets are presented and discussed in detail. The first of these will examine all comets with strong carbon-chain depletions (>4×). Two of these in particular, P/Giacobini-Zinner (the proto-type of the depleted class; cf. Schleicher, Millis, and Birch 1987) and P/Wolf-Harrington (the most highly depleted; cf. Schleicher, Bus, and Osip 1993), were observed by us in their recent apparitions to extend the orbital coverage and search for any variation in depletion with distance. The likely focus of a second paper will be on the similarities and differences among nearly a dozen long-period and dynamically new comets for which we have good orbital coverage. Again, we anticipate completing one of these papers under current funding, but the second (and third, should we discover a particularly interesting sub-set) investigation would be performed under this proposal. Note that, as we conclude our analyses of portions of the database, the reduced data will be made widely available through the Small Bodies Node of the PDS, permitting other researchers to make synergystic studies.

Hale-Bopp: Our observing campaign for Comet Hale-Bopp (1995 O1) began only 2 days after its discovery at a distance of 7.1 AU in July 1995, and continued monthly from April 1996 to May 1997 using Lowell Observatory telescopes. Observations resumed from Perth Observatory in late 1997 and were obtained every 1-2 months (when it was not in conjunction with the Sun) until early 2000 by collaborator P. Birch. We emphasize that CN emission was successfully detected on our first night of observation, and continued to be detected out to 10 AU outbound. A summary of results from data obtained through February 1997 were published in the special issue of *Science* (Schleicher et al. 1997). Even at large heliocentric distances, Hale-Bopp produced more dust than we have previously measured in any other comet at *any* distance. From the observed production rate of the OH, application of the water vaporization model yielded a minimum effective diameter of Hale-Bopp's nucleus of 17 km. However, the actual diameter is likely to be at least 2–3× larger, based on the existence of numerous dust jets which require that much of the surface must be inactive, consistent with various other determinations. The chemical composition of Hale-Bopp is "typical" and matches that of other long-period comets originating from the Oort Cloud.

It was evident, however, that our standard Haser scalelengths did not reproduce the observed radial profiles of any of the gas species during Hale-Bopp's perihelion passage in the spring of

1997 and, based on narrowband images, we (Schleicher et al. 1999) determined that most species' parent and daughter Haser scalelengths needed to be increased by 2-3× the canonical values to reproduce the bulk radial fall-off for each gas species, yielding perihelion production rates 1.1-3.6× larger than otherwise calculated, with water exhibiting the largest correction. In contrast, profiles measured when Hale-Bopp was near 4 AU were generally consistent with canonical values (Rauer et al. 2002). From these results it became evident that at very large production rates the outflow velocities increase rapidly, thereby lengthening the appropriate scalelengths. We have recently begun an analysis (under other funding) of spatial profiles for Hale-Bopp as a function of distance from the Sun which, when completed early next year, will yield appropriate scalelengths to be used in the reduction of all of our Hale-Bopp photometry.

We propose to conduct a full analysis of Hale-Bopp's activity as a function of heliocentric distance, season, and solar phase angle. Already we have seen clear evidence for a strong phase effect at small phase angles, with dust brightening and then fading by 60% as the phase angle goes from 12° to 5° and back to 12°. A significant trend in dust colors with heliocentric distance (or phase angle) is also evident. All of our results will also be intercompared to other, published results, in a manner similar to our Halley analysis (Schleicher *et al.* 1998a).

10P/Tempel 2: The largest dataset of a Jupiter-family comet which we have not yet performed a detail analysis is that of Comet Tempel 2. This comet has long been known to appear nearly stellar as it approached the Sun until its coma rapidly brightens inside of 1.7 AU (cf., Jewitt and Luu 1989; Boehnhardt et al. 1990). To investigate this presumed seasonal phenomenon, we conducted an intensive observing campaign for Tempel 2 from May 1999 to March 2000, obtaining 19 nights of photometry. Given this comet's very small fractional active area which we derived during the 1988 apparition (A'Hearn et al. 1989), we expected to measure a strong asymmetry in production rates about perihelion, and this was indeed the case. Tempel 2 experienced a rapid increase in production rates a few months prior to perihelion. It then decreased very gradually in the 6 months following perihelion, out to our final measurements at 2.4 AU. These data alone imply this behavior was driven by the seasonal changes of a localized source region or regions, similar to what we determined for Borrelly, but with the opposite sense (winter-to-summer rather than Borrelly's summer-to-winter). Our photometric analysis will be combined with planned new observations during the upcoming 2010 apparition (again under separate funding).

Intercomparison of Water Production Rates With Observational Technique:

blah, blah, blah

Time and Effort Summary

Based on the previous discussions, we request 4 months of funding for the PI (Schleicher) and 1.5 months for the Co-I (Farnham) each year. We also request half-time support for a research assistant (currently A. Bair, who has a M.S.). At this level of effort, we expect to complete our second large summary paper during the first year, and begin analyses of our Hale-Bopp dataset. In the second year, we will complete our Hale-Bopp photometry paper along with an additional paper focussed on a subset of the database (such as long-period and dynamically new comets). During the third year, we will complete an investigation of Comet Tempel 2 from the database, to be combined with separately funded new observations of Tempel 2, and we will conduct a detailed intercomparison of our water production rates for numerous comets with those determined from published radio measurements. The proposed levels of effort are based on considerable previous experience with these types of investigations.

Co-I Farnham will participate primarily in the various aspects of the dust analyses and in the Hale-Bopp investigation. He will apply corrections for phase angle to all dust data and, when the observations warrant, use the observations themselves to test the validity of the phase angle correction coefficients. He is also taking the lead in the investigation into grain colors and their relations to numerous parameters, including distance, age, and dynamical class. The PI will conduct the bulk of the DataDesk processing and analyses, perform most of the interpretations, and do much of the writing of each of the papers. The PI will also closely supervise the research assistant who will help with the processing and analyses, and the creation of final tables and figures. Collaborator A'Hearn will participate in many of the gas analyses of the database, and assist in the writing up of results (at no cost to this grant).