DISTANT COMET OBSERVATIONS

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1. Abstract

This paper summarizes the motivation for observing distant comets: they can provide information about the dynamics, collisions, physical and chemical conditions in the early solar nebula. The challenges and techniques of observing faint moving objects at large distances and searching for activity will be discussed. Our state of knowledge about distant comet size distributions, evidence for activity and spectral diversity is presented.

2. Introduction

The observation of distant comets is extremely challenging, but of fundamental importance to the understanding of the formation and evolution of the solar system. A large body of comet knowledge has been amassed from observing short- and long-period comets at perihelion, using imaging and spectroscopic techniques to get information on production rates of daughter species, dust-to-gas ratios and information on the comae and tails of comets. More recently, observations in the sub-mm wavelength regime have opened up a new understanding about parent molecules.

New sophisticated techniques are emerging to infer nucleus properties and primordial composition for comets at perihelion when they are surrounded by a coma partially hiding the nucleus. However, few of these techniques have been verified by direct observations. There is fundamental information about comets and their relation to the early solar system which can only be obtained through observations of distant comets. This chapter will highlight these observations, discuss the observational challenges of distant comet observations and discuss some of the observational results.

3. Importance of Observing Distant Comets

3.1. PLANETESIMAL FORMATION REGION

The short-period (SP) comets have short dynamical lifetimes. Therefore, their population must be replenished in order to maintain a steady-state. Recent dynamical models suggest that the SP comets have low-inclination sources in the Edgeworth-Kuiper region beyond Neptune (Duncan *et al.* , 1988), but that the long-period (LP) and dynamically new (DN) comets formed in the Uranus-Neptune zone and were perturbed outwards (Fernández & Ip, 1981), where they are stored in a vast reservoir, the Oort cloud, before being perturbed toward the inner Solar-System as LP/DN comets. The planetesimals grew by collisional coagulation until they were big enough (10-100m) to decouple from the turbulence between the particle layer and the gas (Weidenschilling, 1997). Many of the collisions were cause by gas drag-induced differential radial velocities, thus a single comet nucleus may have incorporated planetesimals from different heliocentric distances. The dynamical models give information about the formation locations of the different comet classes, and observations of different comet dynamical classes will provide information about the physical and chemical conditions in the solar nebula at different heliocentric distances.

3.2. COLLISIONAL ACCRETION AND SIZE DISTRIBUTION

Collisions in the early trans-Neptunian region probably altered the size distributions of the planetesimals (Farinella & Davis, 1996; Davis & Farinella, 1997), and helped transport the SP comets into the inner solar system. The Centaurs probably represent the transition objects between the Edgeworth-Kuiper belt objects and SP comet populations (Stern & Campins, 1996). While we cannot directly observe this era of solar system formation, we can observe nucleus size distributions and comet nuclei sub-structure size scales (through splitting, and compositional inhomogeneities).

3.3. FORMATION CONDITIONS AND DISTANT ACTIVITY

As the solar nebula collapsed, interstellar grains settled to the midplane. They may have undergone processing of their icy mantles as they fell (Lunine *et al.*, 1991), for instance shock-induced sublimation and volatile recondensation. In the outer part of the nebula temperatures were below

100K, thus the H_2O-ice would have condensed as amorphous ice. Amorphous ice has the ability to trap gases as high as 3.3 times the amount of the water-ice (Laufer *et al.* , 1987). Between 50-125K, these gases are released in distinct temperature regimes in response to the restructuring of the water-ice (annealing). Beginning near 120K and peaking at 137K, the ice undergoes an exothermic amorphous to crystalline phase transition.

The amount of gas which can be trapped is a very strong function of the condensation temperature (see Figure 1). The trapped gases in the planetesimals can thus serve as an extremely sensitive cosmic thermometer for their formation locations. The "thermometer" is read as the temperature (*i.e.* heliocentric distance, r) at which activity is present.

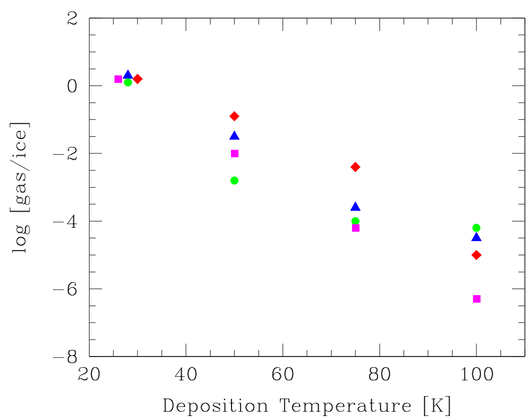

Figure 1. Total amounts of trapped gases in water ice versus deposition for ◇ CH_4; △ CO; ◯ N_2; and □ Ar. Figure after (Bar-Nun & Kleinfeld, 1989)

3.4. ACTIVITY & EVOLUTION

Water-ice sublimation begins near 180K. Low albedo (*e.g.* a few percent) objects can reach this equilibrium temperature near r=5–6AU, thus most comet observations have concentrated on nuclei when they were inside this distance, and active. However, the activity driven by trapped gases in the amorphous ice, by the presence of highly volatile ices, or caused by the amorphous-to-crystalline ice phase transition will occur at much lower temperatures, and much larger distances. Furthermore, it is expected that comets will age (evolve physically and chemically) with repeated close perihelion passages as they lose volatiles. Thus, understanding and comparing primordial comet chemistry requires observations at over a wide range of distances, and observations at large r.

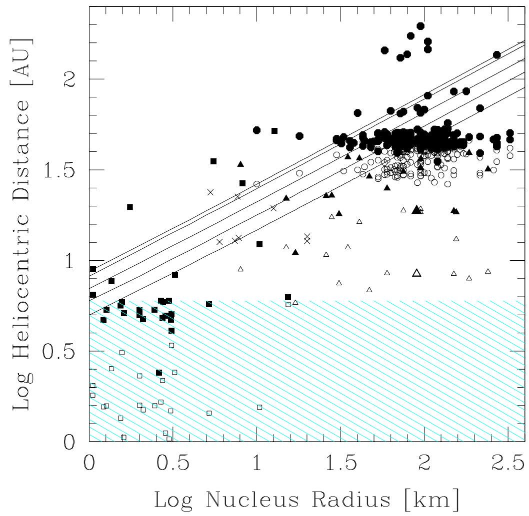

Figure 2. Plot of the curves corresponding to S/N=30 in 1h for telescope apertures 10m, 8m, 4m, 2m, and 1m (top to bottom), for comets of given radii and distances, assuming an albedo of 4%. Open symbols are perihelion observations, and filled symbols are aphelion observations. SP comets for which sizes are known are plotted as □, Centaurs as △ (the larger triangles represent Chiron which has shown activity), and EKO objects as ◯. The LP comets are plotted at their last detection (*e.g.* most distant) as × and the nucleus radii are upper limits since in all case there was coma during the observations. The shaded area of the figure shows the region where H_2O-sublimation is possible.

4. Observational Techniques & Challenges

4.1. EXPECTED BRIGHTNESS

The known SP comet nucleus sizes are typically in the few-km range, and measured albedos suggest that comets are very dark, near 4% (see Meech, 2000 for a review). The expected brightness of the nucleus depends on the solar flux scattered from the nucleus, which is a function of its heliocentric and geocentric (Δ) distances (in AU), the phase angle, α, the nucleus size and its scattering properties (Russell, 1916):

$$p_\lambda R_N^2 \phi(\alpha) = 2.24 \times 10^{22} r^2 \Delta^2 10^{+0.4(m_\odot - m_\lambda)} \quad (1)$$

where p_λ is the geometric albedo, $\phi(\alpha)$ is the phase function, and R_N the radius. Here m_λ is the observed magnitude, and $m_\odot$ is the solar magnitude (in the V filter $m_{\odot V} = -26.74$). The phase function is given by Eqn. 2, where $\Delta m = 0.035\ \alpha$ (Meech & Jewitt, 1987).

$$\phi(\alpha) = 10^{-0.4 \Delta m} \quad (2)$$

By computing the magnitude for which a telescope can achieve a good detection (S/N $\approx$ 30, needed for physical studies) in 1 hour, the above equations can be used to determine the maximum r at which comet nucleii of various sizes can be detected. Figure 2 shows the result of such a calculation. It is clear from the figure that in order to observe comet nuclei as small as a few km in size in the outer solar system requires long integration times with large apertures (see discussion in §4). Some of the known objects (top of the graph) are so faint that they cannot be observed with S/N$\sim$30, even on the largest telescopes.

4.2. OBSERVATIONS & IMAGE PROCESSING

When the comets are faint and total integration times are long, data are taken in an optimal manner if the exposure time of individual images is kept short enough that the stars will not trail by more than a small fraction of the seeing disk. This allows for high signal-to-noise detection of the nucleus after the images are combined in a composite, as well as a sensitive search for any faint coma. The telescope should be dithered between each exposure (*e.g.* offset by up to $20''$–$30''$ in both R.A. and Dec.) so that field stars and galaxies do not fall on the same part of the CCD in each frame. It is therefore possible to combine the images using a median filter to create a dark-sky flat to apply as a correction after the standard flat-fielding has been done using bright twilight sky flats or dome flats. The latter have very high S/N, but do not accurately represent the response of the CCD to the dark sky. When searching for very faint coma, it is critical to get the CCD flat to better than 0.01%, across the chip and this is only possible using auto-flat fielding techniques. This technique is discussed in some detail in Tyson (1990) and Hainaut *et al.*, (1994). The flattening can be further improved using an optimized combination of dome, twighlight sky and night sky flats (Hainaut *et al.*, 1998).

4.3. PHOTOMETRIC PROFILES & COMETARY ACTIVITY

To the first order, the frames are then combined (*i*) using the relative offsets between the frames caused by the dithering and guiding errors – creating a composite image with well-guided stars, and (*ii*) in addition using the comet rates to create a composite image guided at the rate of the comet's motion. The latter requires the image plate scale, orientation, and knowledge of the comet ephemeris rates.

In an uncrowded field, this technique produces two composite images from which surface brightness profiles of both the stars and comet nucleus are computed to search for very faint coma when no activity is directly visible. A comparison of the normalized surface brightness profile of the comet and the averaged profile of several field stars in the untrailed image can be used to place extremely sensitive limits on the presence of any coma or activity (Meech & Weaver, 1996). The surface brightness profile difference between the comet and comparison stars gives an upper limit to the flux, F (Eqn. 3), contributed by a dust coma, where $S_\odot$ is the solar flux through the bandpass [W m^{-2}], ϕ the projected size of the aperture [m], $a_{\rm gr}$ [m] the grain radius, p_v the grain albedo, Q [kg s^{-1}] is the dust production rate, $v_{\rm gr}$ [m s^{-1}] the grain velocity, and r is in AU and Δ in m.

$$F = \left[\frac{S_\odot \pi \phi}{2r^2\Delta^2}\right]\left[\frac{a_{\rm gr}^2 p_v}{v_{\rm gr}}\right] Q \tag{3}$$

However, usually in long sequences of exposures, the comet will have moved over background objects. Techniques of point spread function fitting may be used to effectively remove these objects from the individual frames before combining the images – but only for point sources. A large fraction of the very faint background objects will be galaxies which cannot be easily removed in this manner. Hainaut *et al.* (1994) discusses removal of non-stellar background objects by making artificially trailed comet and "anti-comet" frames. This paper also rigorously discusses the increase in noise expected from the object removal process.

5. Results

5.1. SIZE DISTRIBUTIONS

There are only a handful of sizes which are "directly" measured for any of the comets using the traditional techniques of radiometry. However, even this technique is model dependent, because it relies on assumptions about the optical and thermal phase function of the nucleus (Meech *et al.* , 2000). Most nucleus and EKO size estimates are now made on the basis of the total brightness and by assuming an albedo of 4%. All available size estimates are shown in Figure 3. There appears to be a clear difference in size distributions between the different dynamical classes, however there are many unaccounted for observational biases. All of the observations are affected by selection effects, but this is particularly severe for the EKOs.

The cumulative luminosity function, or number of EKOs per unit area brighter than a limiting magnitude is measured for the magnitude range 20–26 (Jewitt, 1999), and provides important information about the comet size distribution and total number of EKOs. The luminosity function may be fit by a power law size distribution, which has an index between 4.0 $< \beta <$ 4.8, which is probably steeper than the β = 3.5 expected from a collisionally evolved distribution for objects with radii greater than 50km. With better knowledge of the SP comet size distribution, it will be possible to obtain dynamical models for injection of SP comets into the solar system

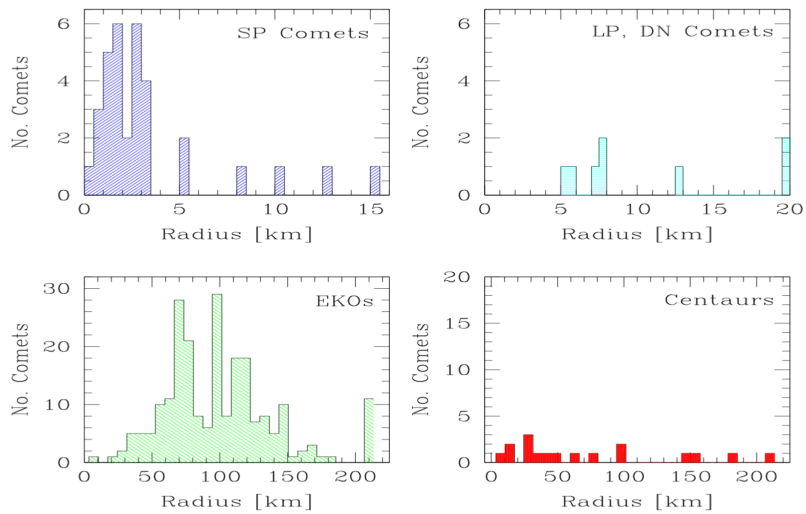

Figure 3. Observed size distributions of the 4 main classes of distant solar system objects

with the estimates of the numbers of small EKOs based on the EKO size distributions (Jewitt, 1999).

5.2. ACTIVITY

Observations over the last decade have shown that cometary activity in LP comets extends well beyond 10 AU (Meech, 1999), and that at least 1 Centaur, Chiron, has extensive activity at large r (Meech & Belton, 1990). It is worth noting that, in some cases, cometary activity was detected at extreme distance, such as in comet 1987H1 (Shoemaker) between 18-20 AU (Meech *et al.* 1996; Meech 2000).

Unsuccessful searches for activity in other Centaurs have been made at different sensitivity levels. There have been intriguing reports of possible activity in EKO objects. At the 1998 ESO workshop on Minor Bodies in the Outer Solar System, Fletcher *et al.* (1998) presented HST observations of EKO 1994_{TB} which showed a 2-σ difference in the surface brightness profile of the EKO and a PSF-star between $0.2''$–$0.5''$ at the 26 mag arcsec^{-2} level. They interpreted the observation as a possible dust coma. The results were preliminary since telescope jitter had not been accounted for. This would have been more important for the EKO which had longer exposure time (by a factor of seven). Subsequent observations of this object from Keck have not revealed any coma in $0.4''$ seeing (Meech *et al.*, 2000).

Observations of the rotational light curve of EKO 1996TO$_{66}$ showed a change in the shape of the lightcurve between Aug.-Oct. 1997 and Sep. 1998 (Hainaut *et al.*, 2000). A proposed cause of the change is that 1996TO$_{66}$

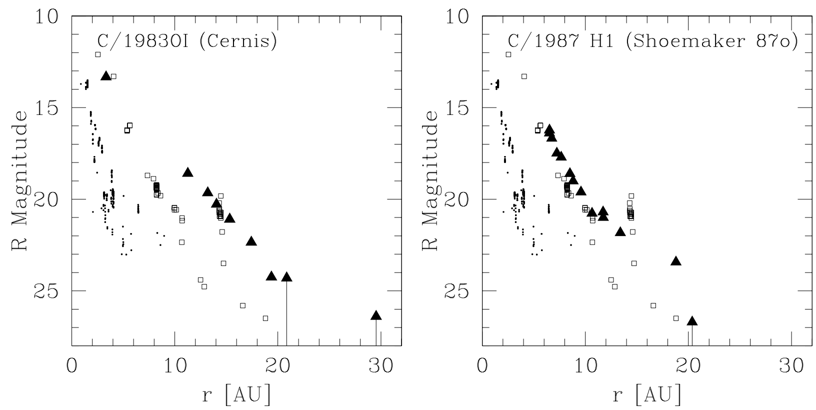

Figure 4. Comparison of the post-perihelion light curves of 2 DN comets (△), with that of P/Halley (□, which displayed an outburst at 14AU), and the Jupiter family SP comets (small dots) showing the large difference in activity levels. The vertical lines indicate that the observation is an upper limit to the brightness.

experienced a phase of cometary activity during the interval between observations. Other possible causes of the change due to complex rotation, or a collision were examined and determined to be highly unlikely. Instead, the lightcurve was easily reproduced by introducing a high albedo spot (caused by deposition of fresh material) on the surface of a bi-axial ellipsoid.

5.3. EVOLUTION & AGING

Long-term observations of distant comets over a range of r from near perihelion out to r=30 AU shows a striking difference in the activity level between LP, DN and the SP comets. Figure 4 shows a comparison of the fading or decrease in activity post-perihelion for two DN comets, P/Halley and a group of SP comets. The DN and LP comets fade much more slowly than do the SP comets and comet P/Halley, which implies a different underlying cause of the activity (Meech, 1999).

5.4. COLORS & SPECTRA

Although limited in number, multi-wavelength photometric measurements of comet nuclei in the optical in the near-infrared, for both the SP comets and the EKO objects show a wide range in color which suggests a diversity of surface types. Tegler and Romanishin (1998) have claimed that there is a division of the EKO objects by optical color into 2 distinct groups. However, other observers do not see a color separation, and this observation awaits confirmation (Barucci *et al.*, 1999). Diversity in colors and surface composition may arise from irradiation and subsequent collisional resurfacing or activity (*e.g.* aging effects), or may result from compositional differences related to different formation locations. Distinguishing between these possible mechanisms will require a larger statistical sample of accurate colors so that trends may be searched for as a function of dynamical age, r, and probable formation location.

Three EKOs have been observed spectrometrically: 1993SC, in the visible (Luu and Jewitt, 1996) and near-IR (Brown *et al.*, 1997); 1996 TL_{66} in the visible and near-IR (Luu and Jewitt, 1998) and 1996 TO_{66} in the near-IR showing the signature of H_2O-ice (Brown *et al.*, 1999). With the growing availability of large telescopes, it is expected that this technique will soon be able to constrain the surface composition of these minor bodies.

6. Conclusions

With the discovery of the Edgeworth-Kuiper Belt, there has been a tremendous push in the planetary community for large telescope time in order to make physical observations of minor bodies in the distant outer solar system. The observations are challenging owing to the small sizes and low albedos of the objects, as well as to the extremely low surface brightnesses of the comae of comets at large r. While critical fundamental information about the chemistry and physics of comets continues to be obtained while they are at perihelion, there is an urgent need for observation of comets at large r in order to understand their primordial composition, the evolutionary effects they have undergone since formation (both physical and dynamical), and to understand the early solar system formation processes and the interrelation between the formation of the cometesimals and the giant planets. Some distant observations are necessary because the objects do not venture into the inner solar system, while other observations at large r are necessary because of the information they can give about volatile processes in the nucleus, and because it is a more direct means of getting information about the nucleus.

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