Review of Recent Literature: Research Concerning Comets*

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This installment of my literature review will present recently published research on Comet 73P/Schwassmann-Wachmann (formerly Schwassmann-Wachmann 3). A relatively faint Jupiter-family comet, 73P was first observed by the German astronomer team of Friedrich Carl Arnold Schwassmann and Arno Arthur Wachmann (Hamburg Observatory, Germany) on 1930 May 2. At that time, the comet was about to pass within 0.0617 AU of the earth, which still ranks ninth on the list of closest known cometary approaches to the earth. For the next 49 years, the comet was lost until re-discovered in August of 1979. After a missed apparition in 1985, the comet was well observed at its next apparition in 1990.

Everything changed in 1995. During an otherwise-poor apparition, the comet was observed to brighten to near naked-eye visibility. Soon CCD observers were recording multiple nuclei as it became apparent that the comet had undergone a significant splitting event. Though most secondary nuclei are short-lived, some of 73P's secondaries not only survived the 1995 apparition but were observed during the next apparition in 2001. With a predicted close approach in May of 2006 rivaling that of 1930, anticipation was high for a spectacular up-close view of this fragmenting comet.

The 2006 apparition did not disappoint. To visual observers, components B and C took on the appearance of a 'double comet' that was reminiscent of comet 3D/Biela in the mid-1800s. CCD observers found more than 70 designated components. If we include the small transitory components being shed nightly by some of the larger components, the total number of observed pieces of 73P would easily number in the hundreds to thousands.

Dust and very small fragments

Some of the larger and brighter components of 73P were observed to actively shed much smaller components during the course of April and May of 2006. In particular, material shed by component B was studied by a group of Japanese astronomers led by Masateru Ishiguro (National Astronomical Observatory of Japan). Their work published in Ishiguro *et al.* (2009) used data taken with the Suprime-Cam CCD imaging instrument on the 8.4-m SUBARU telescope in Hawaii. No fewer than 154 'mini-comets' were observed, with most having been released during a single event around 2006 April 1. Other 'mini-comets' could have been released in later outbursts on April 24 and May 2. V- and R-band photometry produced a mean color index of $V{-}R = +0.50 \pm 0.07$, which is slightly redder than the sun and similar to the color of the nucleus of component C that was derived with the Hubble Space Telescope (HST). The surface brightness profiles of all fragments are consistent with radii in the 5- to 108-m range. The total mass of the detected fragments suggest that 1-10 percent of the mass of component B was lost in the April 2006 outburst events. The motion and diffuse nature of the particles confirm that many of the objects were small and ice-rich; experiencing non-gravitational forces 7-23 times larger than those exerted on component B.

While some of the largest telescopes in the world were trained on 73P, the space-based NASA Spitzer infrared telescope was able to unveil parts of the comet unseen from the earth. On 2006 May 4-6, Spitzer imaged nearly the full extent of the comet's dust trail. At that time, Spitzer was located on an earth-trailing heliocentric orbit at a distance of 0.38 AU from the comet (about six times the comet-earth distance). Two researchers from the California Institute of Technology, William Reach and Jeremie Vaubaillon, presented results on their analysis of the Spitzer data.

Vaubaillon and Reach (2010) modeled the shape of the dust coma of component C. Constraining the dust cone of ejection from the whole sunward hemisphere to a cone of $2^\circ \times 30^\circ$ provided a close match to the observed coma. This shows that most of the dust was ejected in the sunward direction. The shape of the coma of component B was totally different. Though the authors surmise that the difference may be due to the survival of sub-micron-sized particles, they leave a proper study of component B's coma for a later date. Modeling of the width of the dust trail found that ejection velocities of large grains during the 1995 and 2001 passages were twice as high as during other passages. The observed trail is mainly composed of material released during 1995 and 2001. The 1995 splitting event released at least 10 times more dust than previous returns.

Additional Spitzer images taken in March and April 2006, as well as in January 2007, were used in conjunction with the May data by Reach *et al.* (2009). Six fragments were observed in the April data, including the major components B, C, and G. In May, a total of 55 fragments were seen, including the three main components. By January 2007, only components B and C were seen. Component G should have been visible but presumably disintegrated in May, as suggested by ground-based observers. The authors found it difficult to match the fragments seen in the Spitzer data with those observed from the earth. It is surmised that most of the smaller fragments are highly variable in their outgassing

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* This is the eighth installment of a semi-regular *ICQ* column; the last installment appeared in the July 2007 issue of the *ICQ*.

and may only be bright for short periods of time. Variable sublimation rates and fragmentation events would also change the effect of non-gravitational forces on the orbits of the smaller fragments resulting in difficulty in matching objects.

Production Rates and Depletion of Organics

A total of eight nights of narrowband photometry of components B, C, G, and R were acquired by David Schleicher and Allison Bair (Lowell Observatory) at Lowell Observatory. (Their results are presented in Schleicher and Blair 2011). Production rates were measured for OH, NH, CN, C_3, C_2, and for dust in the 'UV Continuum', 'Blue Continuum', and 'Green Continuum' bands. The production rate of H_2O was also derived from the filter data. The filters used were part of the C/1995 O1 filter set. Though component C appeared to be 'well behaved' during the apparition to most observers, narrowband photometry found a large amount of scatter in production rates. The activity slope with respect to heliocentric distance of each species varied more than is usual. The production of C_3 displayed a large amount of scatter even within data taken on a single night. Since the lifetime of the C_3 parent is thought to be less than an hour, rapid changes in production must be occurring due to small outbursts or the rapid rotation of the nucleus. Component C also showed strong evidence of a seasonal effect, with gas-production rates after perihelion being only 20-40 percent of those during pre-perihelion.

Observations of component B are dominated by large outbursts. Two large outbursts were detected beginning about April 1 and May 2, while a smaller event occurred around April 24. Though component B was consistently fainter than component C throughout most of the apparition, it was brighter than component C in their May 9 and 10 data. These dates correspond with a major outburst observed by other groups at that time. Component B may have an even greater seasonal effect than component C, since it was already much too faint to be observed by the Lowell group post-perihelion in September. Component G was only observable after its major outburst around April 6. The May data showed production rates steadily dropping, even as the object approached perihelion. Component R was only observed on a single night. Additional components were searched for but not seen due to their faintness in the narrowband filters.

Water-production rates are consistent with an effective active area of 2.0 km^2 in late February and 4.4 km^2 by mid-May for component C. The rapid increase in effective active area is due to a steep increase in water production with decreasing heliocentric distance. Analysis suggests that this is due to seasonal effect rather than additional shedding events or outbursts. By late September, the effective active area had fallen to only 0.4 km^2. Combining these data with the HST-derived nuclear size of 0.53 ± 0.02 km yields effective active surface fractions of 56% in February, 125% in May, and only 11% in September. Peak water-production rates for component G correspond to an effective active area of 0.2 km^2. The single OH measurement for component R yielded an effective active area of only 0.006 km^2, the smallest value ever measured in David Schleicher's extensive database of comets.

The major finding of the narrowband study of 73P is that the multiple components show the same chemical composition. Though the 2006 apparition was presumably dominated by freshly exposed material, the comet's composition matched that measured during the pre-breakup 1990 apparition. Even though the CN/OH ration matches the mean value of all comets, C_2/OH and C_3 are greatly depleted. This makes 73P one of the most carbon-chain-depleted comets and is similar in this respect to the Jupiter-family comets 21P/Giacobini-Zinner and 43P/Wolf-Harrington. The fact that the interior of 73P shows little difference from the "evolved" surface region suggests that differences in cometary composition are not due to the age of the comet but rather the primordial composition and location of the nucleus at formation.

Yu-ichi Kanda (Osaka Kyoiku University, Japan) and his team used visible-wavelength spectroscopy to derive similar abundances to what was found by Schleicher and Bair (2011). One key difference was a change in NH_2 abundances from a strongly depleted state prior to breakup in 1995 to no apparent depletion in 2006. A normal abundance of NH_2 is inconsistent with 73P being a member of the 21P/Giacobini-Zinner class of carbon-chain depleted comets.

A team led by Michael DiSanti and Geronimo Villaneuva (NASA's Goddard Space Flight Center) measured the abundances of water (H_2O) and carbon monoxide (CO) near 4.65 μm in the near-infrared with the Cryogenic Echelle Spectrograph (CSHELL) at the NASA Infrared Telescope Facility (IRTF) (DiSanti *et al.* 2007) and H_2O, ethane (C_2H_6), methanol (CH_3OH), hydrogen cyanide (HCN), methane (CH_4), and formaldehyde (H_2CO) with the Near-Infrared Cross-Dispersed Echelle Spectrograph (NIRSPEC) at the Keck II telescope (Villanueva *et al.* 2006). Both observations found 73P to be depleted in volatile carbon. The depleted abundance of CO relative to water ($CO/H_2O = 0.5\% \pm 0.13\%$), as well as the fact that CH_3OH is severely depleted while the abundance of HCN is at "normal" levels, is most similar to that observed in the disrupted long-period comet D/1999 S4 (LINEAR). As proposed for D/1999 S4, the depletion in CO may be the result of gas-phase processing of its precometary ices in the inner-Jovian-planet region of the protosolar nebula. During the Deep Impact spacecraft experiment, 9P/Tempel exhibited a change in C_2H_6 abundances from a low pre-impact state to an elevated state within the impact ejecta. Those results suggested that the region of material depleted in carbon only extended to a depth of less than 20 cm. Since the splitting of 73P likely exposed material within the original pre-split nucleus to depths much greater than 20 cm, C_2H_6 abundances were expected to be relatively high and similar to that found in the Deep Impact ejecta. The fact that C_2H_6 is depleted in both component B and component C raises some questions about when and where 9P and 73P formed relative to one another. Possible explanations include the formation of 73P farther from the sun then 9P or its formation at a later stage when the clearing nebula had allowed the penetration of significant extrasolar x-rays.

Similar to the above results, Hitomi Kobayashi (Kyoto Sangyo University, Japan) also found components B and C to be depleted in C_2H_6 and C_2H_2. He also concludes that the formation region of 73P was different from that of typical Oort-cloud comets but similar to that of D/1999 S4 (LINEAR). Since both comets were depleted in organic volatiles, it is possible that they both formed relatively close to the sun at distances of 5-10 AU and were subsequently ejected into the scattered disk and Oort cloud.

Sub-millimeter Observations

The Heinrich Hertz Submillimeter Telescope on Mount Graham in Arizona was used to observe the production of HCN. L. Paganini and M. Drahus (Max-Planck Institute, Germany) analyzed the abundances and distribution of HCN. Paganini *et al.* (2010) utilized sub-millimeter observations of HCN in conjunction with narrowband imaging with the Lulin Observatory 1-m telescope in Taiwan to determine the source of CN in component B and component C. Comparing the distribution of dust, HCN, and CN for components B and C yielded a correlation between HCN and CN. These results suggest the formation of CN from HCN, and not from dust or ices released from the dust. HCN was also used by Drahus *et al.* (2010) to measure the rotation period of the nucleus of component C. HCN was selected because it is believed to sublimate directly from the nucleus and produces the brightest emission lines for ground-based sub-millimeter observations. They found that periodicities between 3.0 and 3.4 hr corresponded with the likely rotation period. If correct, component C has the fastest known rotation period of any comet, and this suggests that large centrifugal forces caused the 1995 splitting event. Such a rapid rotation period is informative with regards to the bulk tensile strength of the nucleus, which is found to be between 14 and 45 Pa.

Lightcurve Analysis

Analysis of the lightcurves of 73P and component C in 1990, 1995, and 2001 by Ignacio Ferrín (University of the Andes, Venezuela) was published by Ferrín last year. The pre-split comet had a "photometric age" of 55 cy (1 cy = 1000 years), which was much reduced after splitting to 21 cy in 1995 and 18 cy in 2001. The reduction in photometric age means the lightcurve now has the characteristics of a younger comet, suggesting that the 1995 splitting event has rejuvenated the activity of the comet.

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CORRIGENDA TO PUBLISHED OBSERVATIONS

Below are listed some observations that were published/archived with date errors sent by the observers and not caught in the editorial process. All of these have been corrected in the master database.

• Comet C/2002 Y1, *ICQ* No. 127 (p. 139): observers TOT03, KUL02 HAD01, BAL08, and SIP, *for* year 2002 *read* 2003. • Comet C/2002 T7, *ICQ* No. 129 (p. 30): observer *MOR*, *for* year 2001 *read* 2004. • Comet C/2007 W1, *ICQ* No. 147 (p. 129): observer *DIJ*, *for* 2008 95 04.89 *read* 2008 05 04.89. • Comet C/2006 OF2, *ICQ* No. 149 (p. 34): observer *BOU*, *for* year 2002, *read* 2008/ • Comet C/2006 W3, *ICQ* No. 149 (p. 35): observer *BOU*, *for* year 2006, *read* 2009. • Comet C/2008 T2, *ICQ* No. 149 (p. 38): observer *BOU*, *for* year 2002, *read* 2008.