ASTRONOMY BEAT

Hubble Encounters Comet ISON — How Science Trumped Spectacle

Max Mutchler (*STScI*)

The so-called "Comet of the Century"

I never heard any of my professional colleagues refer to C/2012 S1 (better known as Comet ISON) as the "Comet of the Century." I have avoided the term, and felt obligated at every opportunity to temper the expectation that ISON could become as bright as the Full Moon. Early on, I was quoted in local Baltimore news media saying "we prefer to wait" and "comets are unpredictable" and "you don't have to oversell this comet," which is the tone most scientists had all along. But this grandiose term stuck, regardless, and the heightened expectations drew increasing attention from the public and the science community alike. This in turn helped justify a massive worldwide observing campaign, making ISON one of the most carefully studied comets of all time.

The hype certainly drew the attention of the Hubble Heritage team, of which I am a member. Since 1998, Heritage has been tasked with using Hubble observations and archival data to shamelessly produce evocative images — the iconic and awe-inspiring vistas that Hubble is famous for. In this article, I will share some personal anecdotes and perspectives from the Hubble ISON observations, a semi-coordinated campaign involving several observing programs in addition to Heritage. There is no attempt here to comprehensively summarize all the Hubble ISON observations or results, which are available via the links provided.

Figure 1: View of the Hubble Space Telescope over the Sahara Desert. *[NASA]*

For scientists, the excitement over ISON wasn't only the possibility of being dazzled in our backyards by a brilliant comet. Although we'd certainly enjoy such a spectacle along with everyone else, the

scientific interest had a different focus. It was the prospect of a "dirty snowball" from the distant Oort Cloud — the very edge of our Solar System — on its first trip in towards the Sun (unlike the periodic comets which have been weathered by the Sun multiple times). This was a relatively undisturbed sample of material from when the Solar System formed over 4 billion years ago. What is it made of? Could it help explain how Earth got its oceans? This comet was also a "sun-grazer," heading for a searing trip right through the Sun's corona. If it survived the Sun's intense heat, a good amount of its material would be liberated from the nucleus, allowing it to be analyzed over many weeks by an array of scientific instruments on Earth and in space. That would be the Comet of the Century scenario, where fantastic tails of dust and sublimated ices would wow us all shortly after perihelion. If the comet nucleus didn't survive the ordeal — if instead the Sun's intense tidal forces ripped the comet apart — then all of the dust and ices would be liberated very quickly. It might then dissipate so quickly that there would be a narrow window of opportunity to study it further.

I had been semi-joking all along that I hoped the comet would disintegrate well before perihelion, while it was still observable by Hubble (far enough away from the Sun). Hubble is uniquely qualified to perform such a cometary post-mortem, with great resolution and sensitivity, as it has done for several comet breakups in the past. But a disintegration would also provide us an exit strategy from the corner of high expectations that we'd all been painted into, by being spectacular in a different way. It would be a convenient escape clause during conversations at upcoming holiday parties, where friends and family would surely be buttonholing us as to why ISON never did become the Comet of the Century.

The Heritage team starts scheming

Although the decision process of the Heritage team is primarily driven by aesthetics, we are not oblivious to the scientific value of the data we produce — me in particular. I am an expert with Hubble's cameras. I have helped develop many of the observing strategies and data reduction techniques (e.g. "dithering and drizzling") that generate the highest data quality in Hubble imaging. My role in the Heritage team is to employ all of our best practices in designing the observation details which make for awe-inspiring press release images, and also add great scientific value to our data archive. I also specialize in imaging Solar System objects with Hubble, which presents unique challenges in every phase of the process. These rowdy objects can be moving and rotating quite fast. They must be tracked by the telescope, which makes observing them a very different game than for the stately nebulae and galaxies which sit very still while getting their picture taken by Hubble. So when Zolt Levay (the Heritage team leader) and Keith Noll (the team's original founder) suggested that we conduct a campaign to observe Comet ISON at various epochs on its sunward journey, well, they had me at "hello" in that telecon. This was right in my wheelhouse.

From its vantage point above Earth's atmosphere, Hubble could provide the most sensitive and high resolution imaging of the comet nucleus — the source of all the action. We pitched the idea of a Heritage imaging campaign of Comet ISON to our Director, Matt Mountain, who graciously granted us six orbits (the Hubble currency, 96 minutes each) of his Director's Discretionary (DD) time. He granted us another five "target-of-opportunity" orbits to be used only if the comet disintegrated. He also approved several other DD observing programs for ISON, and later our Time Allocation Committee (TAC) approved even more.

Although most of the Heritage imaging of Comet ISON tracked the moving target as usual, I convinced the team to expend one of our precious Hubble orbits to conduct a rather unorthodox observation. For several years I had been suggesting that we deviate from

our own best practices just once, and image a small Solar System object with a fixed pointing (tracking the essentially stationary background stars rather than the comet). My "mad scientist" idea was to intentionally allow the moving object to streak through the image. The nearby planetary object would actually carve a parallax S-curve through the image, which reflects the motion of the object itself and also that of Hubble swinging from one side of Earth to the other during its orbit. The static pointing would also mean that a much deeper background would be captured, since the more distant stars and galaxies would not streak and get blurred out. We could never match the Ultra Deep Field image on the cosmological far end, but we could achieve a different sense of vertigo by including a Solar System object on the near end — something essentially on our doorstep in the vast cosmic scale. It gets tougher each year for the Heritage team to find ways to top ourselves, and I felt this image would provide a truly unique perspective. I was originally thinking of applying this observing strategy to a near-Earth asteroid, but Comet ISON presented an even better opportunity.

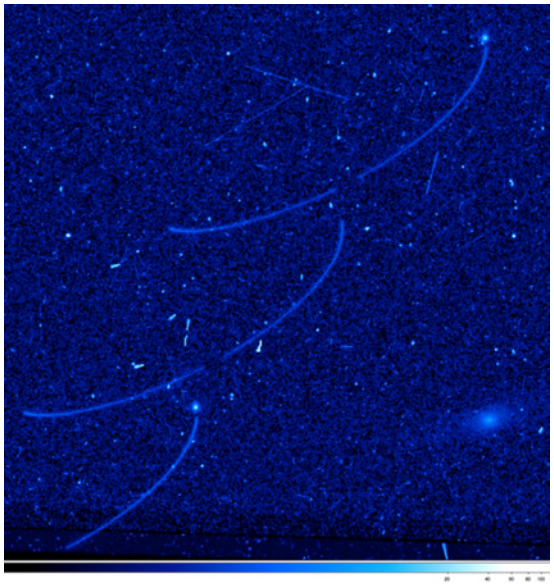

Figure 2: A serendipitous asteroid moving through a series of fixed-pointing Hubble images of a galaxy. The intended target, a large galaxy, is not visible here. But a much more distant galaxy is visible at lower right. Other unwanted artifacts such as cosmic rays and detector features are also evident, and the asteroid would get rejected from the image along with them. *[Mutchler]*

Actually, we unintentionally obtain Hubble images like this quite frequently. I have seen many asteroids and artificial satellite trails in single Hubble images of galaxies. But I dutifully combine multiple images to reject them along with all the other "unwanted artifacts" (cosmic rays, bad pixels, etc.) to create clean images. For once it would be intentional, and I would preserve the moving object instead of rejecting it along with the other artifacts.

The Heritage team ended up producing a nice sequence of ISON images at several key epochs. They all served our purposes, complemented the other Hubble ISON observing programs, and generated interest from the public. But there were some unexpected reactions from the public, too.

Joy of Looking

Before our Heritage observations got started, one of the other approved DD programs first imaged ISON with Hubble on April 10, 2013. The observations were led by my colleague Jian-yang Li of the Planetary Science Institute, whom I have collaborated with on many Hubble observations. So I was delighted to assist Jian-yang with this first glimpse, and produce the cleanest and deepest possible image from the raw data. Li's image was released on April 23.

I was surprised by how much ISON already looked like a full-fledged comet with coma and tail, even though it was still about as far away from the Sun as Jupiter. Li and his team estimated from these early images that the nucleus was probably just a few kilometers in diameter, at most. This was the first hint that, in terms of size, ISON was no supercomet. For comparison, the nucleus of Comet Hale-Bopp was estimated to have a diameter of 70 km. By subtracting a model of the comet's coma, Li was also able to identify a sunward jet (Li et al., 2013).

But to say I was delighted to be included in this first glimpse is actually a gross understatement, so let me be more truthful. My name is Max, and I'm an addict. For so long now, I have had such a steady

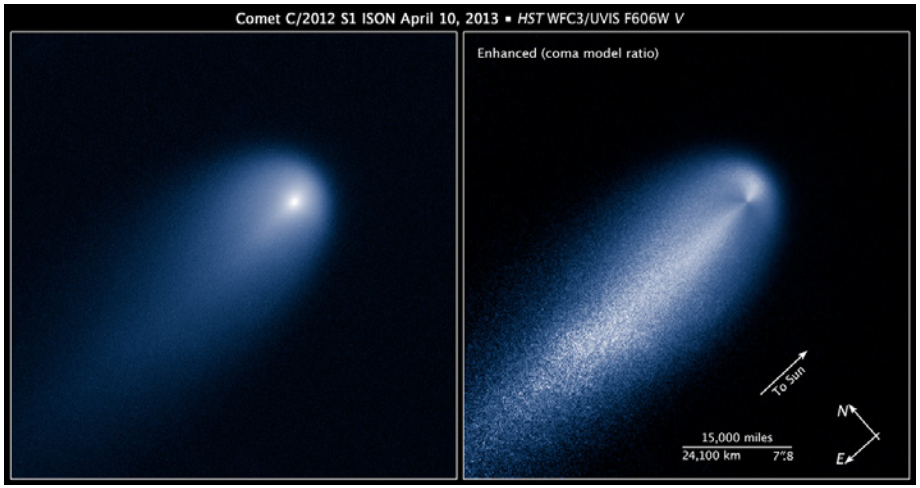

Figure 3: First Hubble image of Comet ISON on April 10, 2013 by Li et al. Although almost as far from the Sun as Jupiter, ISON already displayed a significant tail and sunward jet (evident at right, after removing a model of the comet's coma). *[NASA, ESA, and Z. Levay (STScI)]*

fix of brand new Hubble images to gaze upon — ones that nobody else has seen yet — that I can't fathom life without it. That moment when I am pulling up a new Hubble image for the first time is an endless thrill for me — the best part of my job, by far. It taps directly into why I became interested in astronomy in the first place. And when I pause to think of everything it took to produce that image on my computer screen – Lyman Spitzer, spacewalking astronauts, all the dedicated people operating Hubble for over 23 years — the line from Wayne's World comes to mind: *"I'm not worthy! I'm not worthy!"*

But when I am responsible for designing the observations, there is another visceral feeling that surges within me just before I display a new image on my computer screen: *fear*! I fear that the image will be blank, thereby wasting precious Hubble time and testing the patience of my collaborators. Sometimes a failed observation is caused by the telescope itself, which typically leads to an automatic "do over." But more often it is human error, and moving targets present extra opportunities to mess up. In that case, a "do over" might not be granted. I haven't produced any unintentionally blank Hubble images yet, probably because of the fear and paranoia that I proceed with at every step of the process.

New Hubble data can be downlinked, and arrive on my computer screen, at any hour of the day or night. So these moments don't always happen in my office at work. For example, I have also enjoyed that first glimpse of amazing new Hubble images at home — perhaps on my porch, or at the wet bar — and during long hours in airport terminals and hospital rooms. One of the ISON images arrived while I was vacationing at my sister's home in Wisconsin. Others arrived while most members of the various Hubble ISON observing teams were at a planetary science conference in Denver. It was a rarity for us to be able to inspect and discuss the new data in person. Collaborators are often scattered around the globe, sharing our first quick-look at new data across various time zones, and with each of us at random points in our daily lives.

I often think of my favorite Hubble observations in terms of the events surrounding me at the time I was working on them — the settings and people who shared with me this simple joy of looking, and gave the moment even greater personal richness and relevancy.

Heritage gets going

On April 30, the Heritage team obtained our first images of ISON — it was the fixed-pointing observation that I had advocated for. Shortly after, on May 8 we obtained our first tracked imaging. The latter was more straightforward to process, and we released it on July 2.

The main goal of our tracked imaging was to get another deep and clean image of the comet — similar to Li's image but one month later. But in addition to creating a clean image by combining all the single frames (and rejecting the background stars), the Heritage team constructed a movie from the series single images too. We only gathered

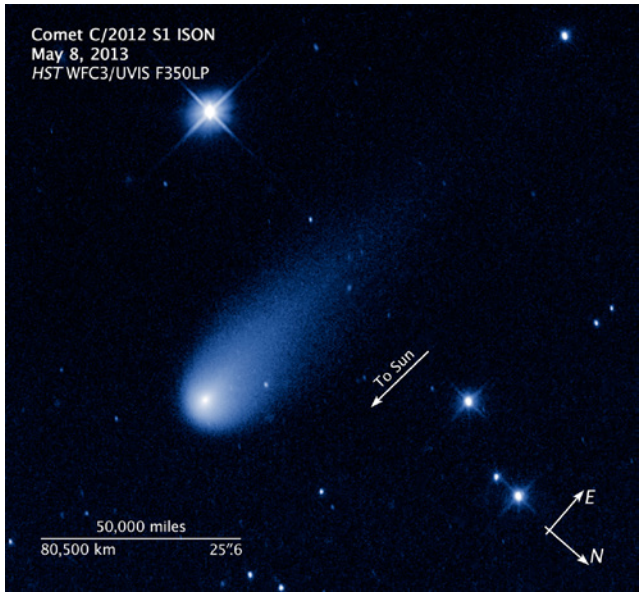

Figure 4: Tracked image of Comet ISON on May 8. *[NASA, ESA, and Z. Levay (STScI/AURA)]*

images with one filter, so we could not make a true color image from this data. And the background was not deep since the stars and galaxies got streaked while tracking the comet. But with some extra processing steps we were able to produce our first movie conveying the motion of the comet.

Meanwhile, the Heritage team was working hard to make a color composite image, and another movie, from the deeper fixed images from April 30. This required some careful post-processing to deal with the fact that the comet streaked a bit during the exposures. We released the color composite image on July 25. Again, the series of single images was also made into a movie that was released later.

On May 7, another ISON program led by Dean Hines (also at STScI) obtained some polarized images. His observations revealed some interesting scientific results, which are published (Hines et al., 2013). But they initially drew public attention for another reason. Unlike the Heritage data, Dean's images were made immediately available in our archive. Eager amateurs were quick to download the data, and some started wildly misinterpreting it before Dean's team had time to carefully analyze the data and publish their findings.

The single raw images that come from Hubble are loaded with artifacts that must be carefully rejected, usually by combining multiple images. Dean's data suffered a common problem whereby moving-target images get automatically pipeline-processed as if they were fixed-target images. In Dean's case, this lead to partial rejection of the comet itself. This improperly combined version of the data is stored in our archive, but typically ignored by professionals anyway. We are able to get better results by doing our own careful processing of the raw images offline, and again in this case I performed the data reductions for Dean.

Figure 5: Color composite image made from deep fixed-pointing exposures on April 30, 2013 *[NASA, ESA, and the Hubble Heritage Team (STScI/AURA)]*

To the untrained eye, a badly-cleaned image can create the illusion that something incredible is happening with the comet. Dean and Zolt carefully responded to such misinterpretations posted to social media, and it eventually seemed to quiet the misguided notion that the comet may already be breaking up. We certainly didn't want to squash anyone's enthusiasm, but it was important to steer the dialogue away from misunderstanding and confusion. This event foreshadowed the next round of over-eager public attention to our Comet ISON images.

Filling the void

Throughout history, comets have been a source of misguided fear and hysteria, based in ignorance of their true nature. Despite our much greater understanding of them now, and the advent of the Information Age, unfortunately it seems that misinformation often still travels faster and farther than credible information. With our Hubble observations of ISON, we found we were not fully inoculated from this history of hysteria.

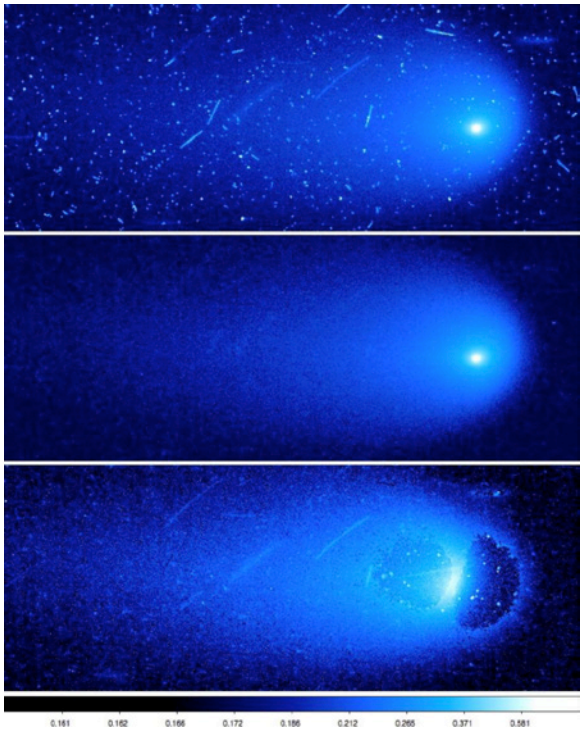

Figure 6: Top: raw image with many artifacts (cosmic rays, star trails). Middle: version of the same image with artifacts rejected offline by the author. Bottom: automatic pipeline processing with part of the comet rejected. *[Mutchler and Hines]*

A primary goal of our series of Hubble Heritage ISON observations was to keep the storyline alive and interesting throughout the unfolding event. One challenge was the fact that the comet could not be observed by anyone from early May until late summer or early fall, because the Sun was in the way. This was one of the reasons we slowly rolled out our early Heritage imaging during the lean months of June and July — to fill the void.

But others were even more actively trying to fill the void during this period. There were several claims from dubious sources that the comet had already "fizzled" or started to disintegrate. None of the scientists studying ISON with Hubble found these claims convincing, and on October 6 Hubble quickly dismissed the notion entirely with another image showing the comet fully intact. Interestingly, the jet seen early on by Li had disappeared.

But we also had to deal with the ramifications of even more dubious claims about our images. Although the Heritage team was trying to stay ahead of the story, by releasing more details and background information than usual via our ISONblog, others were trying even harder to weave their own stories with our images.

The primary source of the trouble was not our press release image. Rather, it was the actual data that the color composite image was made from. I had ingested my versions of the fixed-target images — the ones with the comet streaking in them — to our archive, and again some over-eager segments of the public were quick to misinterpret what they saw. They saw three streaks in a combination of three images. In the composite press release image, multiple images were composited to provide more accurate color to the static background stars and galaxies. The comet itself was rather colorless, and the three streaks were caused simply

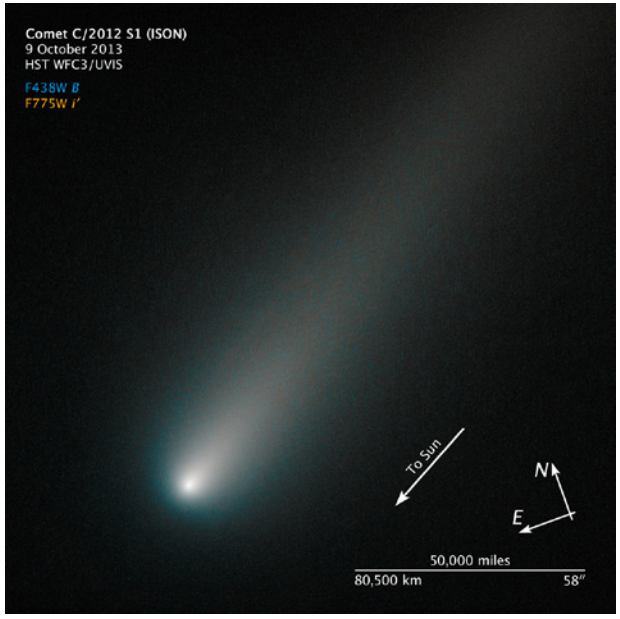

Figure 7: Hubble image from Oct 6, released on Oct 17, nucleus still intact! *[NASA, ESA, and Z. Levay (STScI/AURA)]*

by the motion of the comet during the exposures. So we added only one of the three images of the comet to the final composite image, to represent the comet accurately. There were several YouTube video authors who found this all very suspicious. They speculated that it meant the comet was really in several pieces, or it was an alien spaceship, and that our image processing was a cover up.

Again, none of these wild claims seemed to travel far outside the tightly knit circles of conspiracy-theorists and UFO-watchers. But it gave us some trouble when that audience crashed our archive servers, by all-at-once trying to get a look at the data for themselves.

In the end, this became a "teachable moment" that allowed us to reveal more about the work we do behind-the-scenes to produce the Hubble images people see in our press releases. The images don't produce themselves. This is a real craft that requires skill and effort, and there is nothing sinister about reducing raw data and processing it into composite images. It is necessary to suppress the artifacts and convey the best information from them — as we have done for almost every Hubble image you have ever seen.

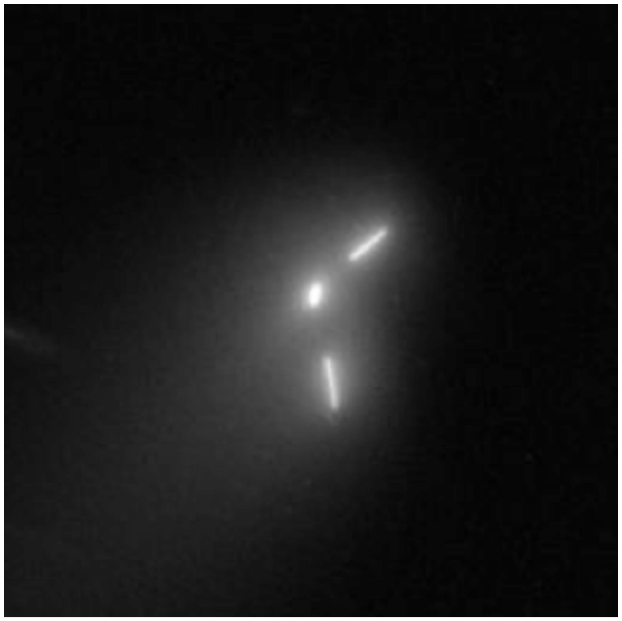

Figure 8: Close up of summed image of three exposures, showing ISON's nucleus forming elongated streaks, which curved during the exposure sequence due to parallax. *[Hubble Heritage team]*

We took our final pre-perihelion image on November 2, with the comet looking bigger and brighter. Again this time we used two filters so we could produce a color composite image.

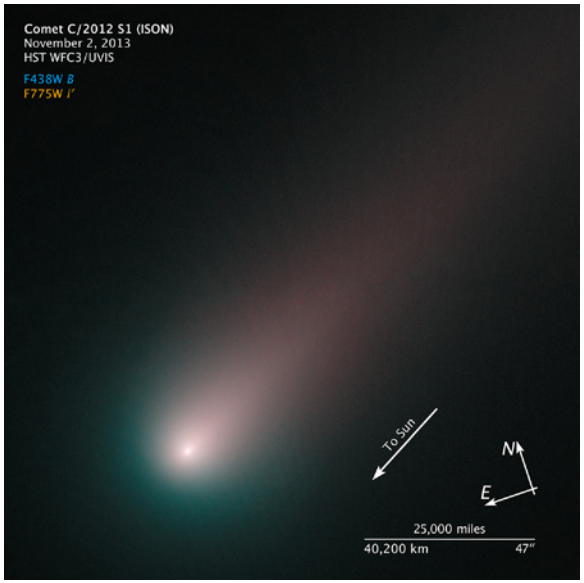

Figure 9: Final pre-perihelion Hubble Heritage imaging of Comet ISON on Nov 2, just before HST solar avoidance begins. *[NASA, ESA, and Z. Levay (STScI/AURA)]*

By this time, ground-based observers were producing the most spectacular wide-field images of the comet, while with Hubble's small field-of-view we continued to focus on the nucleus and coma. Although the comet was closer, the bigger and brighter coma made it more difficult to estimate the size of the nucleus. But several other observatories had independently estimated the nucleus to be quite small — the lowest estimate was even under one kilometer in diameter. If those lowest estimates were correct, it probably helps explain what happened next, as ISON reached its blistering perihelion on Thanksgiving Day, November 28.

Leftovers from a Thanksgiving Turkey

It felt a bit odd to be on holiday, and a spectator, at the most crucial point in this storyline. It had been a busy nine months of cyclically designing Hubble observations of Comet ISON, reducing and analyzing the images, and then planning the next round. If ISON survived its perihelion passage, we would be ready to make more Hubble

observations starting in mid-December. But with Hubble unable to observe ISON while it was near the Sun, I was free to enjoy the Thanksgiving holiday in the Catskill Mountains of New York.

Like so many others, in between more traditional holiday activities I found myself glancing repeatedly at my electronic devices to monitor the natural drama unfolding near the Sun. The magnificent SOHO and STEREO spacecraft brought the whole world along for the ride. I was riveted by the twitter feed of Karl Battams (@SungrazerComets) of the Naval Research Labs who performed brilliantly as Master of Ceremonies.

But over the course of the day, as anyone paying attention knows, Comet ISON did not fully survive this Moment of Truth. At first it seemed the comet may have disintegrated around perihelion and completely disappeared. All along, we knew this was one possible scenario. But that slow realization, coupled with the tryptophan coursing through our veins, was making many of us ready to curl up in a ball and close our eyes. I started coming to terms with the fact that there would be no post-perihelion for ISON — the game was over.

Then *something* emerged from the Sun. It looked quite different than the comet we saw before perihelion. It was much more diffuse, and already fading fast as it left the view of SOHO and STEREO.

The Heritage team had unused Hubble orbits remaining, as did several other ISON observing programs. But as I came back from the Catskills with my family, I was assuming that there would be nothing left for Hubble to observe by mid-December. Or at least that whatever is left would probably be impossible for Hubble to detect, so we couldn't easily justify using up any more orbits. But spreading throughout news and social media rather quickly was the notion that only Hubble could close the deal — that we had to look for remnants of Comet ISON. At STScI we chuckled about it, since it wasn't coming from us. But the observations were quickly authorized, and the death watch was on. So with strategic input from another colleague and Hubble ISON observer, Hal Weaver from Johns Hopkins Applied Physics lab (JHU/APL), the Heritage team prepared another observation for Dec 18.

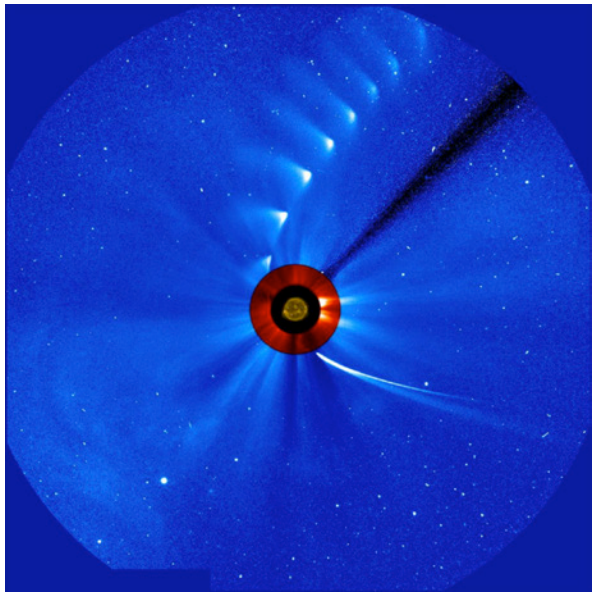

Figure 10: Comet ISON comes in from the bottom right and moves out toward the upper right, getting fainter and fainter, in this time-lapse image from the ESA/NASA Solar and Heliospheric Observatory. The image of the sun at the center is from NASA's Solar Dynamics Observatory. *[ESA/NASA/SOHO/SDO/GSFC]*

We wondered exactly where we should point Hubble, with it's narrow field-of-view. Should we point where ISON's nucleus *would have been* on Dec 18, or could any remnants have been driven off that course by a flurry of randomly-pointed jets during a violent breakup? Would someone else be able to detect fragments that could inform our pointing? Nobody was able to, and some of the best efforts would come too late for us anyway. So Hal's strategy was to image two spots: the one where simple orbital mechanics says the intact nucleus would have been, and another spot dictated by models that attempted to account for non-gravitational forces.

On December 20, we announced via ISONblog what we suspected all along: there was nothing left of ISON that Hubble could detect. This was coupled with some equally null radar results from Arecibo Observatory the same week. It was time to declare that this massive worldwide and space-based observing campaign had most likely reached an end — with a whimper, and such a far cry from the

hoped-for blaze of glory. This was essentially non-news at this point. So our blog post whimsically referenced an old *Saturday Night Live* slap at another overblown death watch: "This breaking news just in: Comet ISON is still dead!"

Success and failure

Among my Thanksgiving cohorts was an inquisitive nephew who reminded me that my very first significant interest in astronomy began when I was about his age, and it was a comet. In first grade, I got swept up in the hype over Comet Kohoutek — an earlier "Comet of the Century" which was ultimately considered a dud. This memory gave me some further perspective on Comet ISON, which will now now go down in history the same way.

Kohoutek didn't sour me on astronomy. It actually helped reel me in to the world of ideas and science, and to realize that the adults didn't have everything all figured out. There was plenty of mystery and unpredictability in the world, and I felt invited to think about it and pursue it. For a dud, Kohoutek served me pretty well. It helped set me on a course that, all these years later with ISON, completes a personal orbit of sorts.

As the Sun came up over the mountains on the day after Thanksgiving, I knew Comet ISON — or remnants of it — were very nearby it. That I would not be dazzled by ISON with my own eyes in the coming days was really only slightly disappointing to me. I stood there, immersed in fresh morning air that included a light snowfall, and the amazing sound of water rushing rapidly down the Esopus Creek. Equally dazzling to me is the notion that I was standing there awash in ancient comet remnants — the snow, the creek, in my coffee, and in me. We have replaced hysteria about comets with the hard-won enlightenment that they likely played a significant role in the origin of life on Earth. They might have delivered water and amino acids, and their scientific study has certainly delivered us from ignorance. This is a profound success by any measure, and this unparalleled ISON observing campaign has kept this proud history going.

I have great admiration and appreciation for the many scientists and amateur astronomers who have been diligently studying ISON over the past year. I hope that ISON's legacy will be similar to Kohoutek's in revealing the process of science to kids, and inspiring the next generation of explorers. Each new comet is like another fleeting gust of mountain air rushing past us, whispering secrets of the universe in our ear. So don't dwell on the untimely death of ISON. Instead, consider ISON a reminder to keep your eyes, ears, and mind wide open for the next secret to be revealed.

> *Who casts not up his eye to the sun when it rises? But who takes off his eye from a comet when that breaks out? Who bends not his ear to any bell which upon any occasion rings? No man is an island, entire of itself; every man is a piece of the continent, a part of the main. Any man's death diminishes me because I am involved in mankind; and therefore never send to know for whom the bell tolls; it tolls for thee*. — John Donne

About the Author

Max Mutchler is a Research and Instrument Scientist at the Space Telescope Science Institute in Baltimore. Max is an expert on Hubble's cameras, and has been involved in a wide range of scientific observations with them. As a member of the Hubble Heritage team, he has helped produce many of the iconic images that Hubble is famous for. In particular, Max loves the challenge of observing Solar System objects with Hubble.

References

- Hines et al. http://arxiv.org/abs/1311.4896
- Li et al. http://arxiv.org/abs/1311.0826

Appendix: links for Hubble observations of Comet ISON

- ISONblog at STScI:
  http://hubblesite.org/hubble_discoveries/comet_ison/
- Hubble ISON press releases:
  http://hubblesite.org/newscenter/archive/releases/2013/14/
  http://hubblesite.org/newscenter/archive/releases/2013/24/
  http://hubblesite.org/newscenter/archive/releases/2013/31/
  http://hubblesite.org/newscenter/archive/releases/2013/42/
- Related Google hangouts on July 17, Aug 14, and Oct 17:
  https://www.youtube.com/watch?v=xMagVxn3ILo
  https://www.youtube.com/watch?v=K5ZY_hzxz9c
  https://www.youtube.com/watch?v=YeN3W3WfEn4
- Heritage collection of High Level Science Products (actual data in FITS format):
  http://archive.stsci.edu/prepds/ison/
- Baltimore Sun article:
  http://articles.baltimoresun.com/2013-09-10/health/bs-hs-comet-ison-20130907_1_international-scientific-optical-network-comet-ison-epoxi
- WJZ-TV interview:
  http://baltimore.cbslocal.com/video/8820387-hubble-telescope-helps-astronomers-observe-comet-of-the-century/
- Discovery special segment:
  http://watch.discoverychannel.ca/discovery-presents/discovery-presents-hunt-for-a-super-comet/#clip1054726
- Hubble's Comet SW3 disintegration movie:
  http://www.spacetelescope.org/videos/heic0605b/ ✦

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