THE PUZZLING DETECTION OF PLUTO IN THE X-RAY BY *CHANDRA.*

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Introduction: Pluto, the first and largest discovered Kuiper Belt Object, lies at the outer edges of our solar system and was the target of the 14 July 2015 flyby by the NASA New Horizons (NH) mission [1]. Pluto is known to have an atmosphere which changes size and density with its seasons [2,3] and preliminary model results models of its atmosphere from the flyby [1,4,5] reveal a majority N_2 atmosphere with a condensed exobase of ~1000 km height and a low escape rate of < $7x10^{25}$ mol/sec [6]. Pluto is also immersed in the interplanetary solar wind (SW), and how it interacts with the wind depends on the state of its atmosphere. This physical situation is similar to that of Mars in the SW at 1.5 AU, although the presence of a long extended plasma tail streaming downstream from Pluto may have aspects of the comet case at 1 AU [7-14].

Given that most pre-encounter models of Pluto's atmosphere had derived a near-body thick exobase surmounted by a gravitationally unbound layer losing $\sim10^{27}$ to 10^{28} mol/sec of N_2 and CH_4, similar to the neutral loss rates for Jupiter Family Comets (JFC) comets at 1 AU, we believed that it would be worthwhile to try to detect X-ray emission created by SW-neutral gas charge exchange interactions around Pluto. We expected a much lower count rate, as Pluto resides at r_h = 30-50 AU, even though a SW flux decreasing as $1/r^2$ causes a neutral's lifetime vs. charge exchange ~ r^2 while the projected *Chandra* pixel size also increases as r^2 and roughly the same number of total emitting x-ray centers would be in each *Chandra* projected 12,000 x 12,000 km^2 pixel for Pluto as for a "typical" JFC comet observed by *Chandra* at 1 AU (e.g., 2P/Encke observed by *Chandra* in 2003 [8] or 9P/Tempel 1 observed by *Chandra* in 2005 [9]). Based on our previous JFC comet x-ray detections, we expected a total *Chandra* count rate for Pluto on the order of 3 x 10^{-5}. With an estimated chip background rate of ~ 10^{-4} cps, the major concern with observing Pluto was that any local heliospheric or instrumental backgrounds could dominate the observed X-ray signal.

In late 2013 we received 35 ksec of *Chandra* time to spectrophotometrically image the system. Given the *Chandra* visibility window constraints for the Pluto system, the first observations were possible starting mid-February 2014. To maximize the potential signal from the *Chandra* observations, we worked to schedule the *Chandra* Pluto observations at a time when the variable SW fluence as extrapolated to Pluto's location would be near its maximum. We used the SW trends measured by the NH Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) and NH SW Around Pluto (SWAP) instruments, which were ~4 AU upstream of Pluto at the time of our observations and had been monitoring the SW for almost a year previously while NH was in its "hibernation mode." At the time of the observations we had received downloaded NH data only through Oct 2013, and the need to extrapolate the SW conditions forward in time to late February 2014 introduced significant uncertainties in the extrapolation.

24 Feb 2014 Observations: *Chandra* Advanced CCD Imaging Spectrometer (ACIS) - S-array (ACIS-S) spectral imaging observations of the Pluto system were obtained under *Chandra* program #15699 using a single telescope sky pointing from 24 Feb 2014 02:02:51 to 12:17:15 UT. The Pluto system was centered near the "sweet spot" of the *Chandra* S3 chip, where the instrument spectral imaging response is best behaved. *Chandra* did not track with Pluto, but instead tracked sky-fixed targets at the nominal sidereal rate. The instrument was operated in Very faint (VF) event-detection mode, and a total of 8700 counts were detected on the S3 array during 35 ksec of observing. By filtering the detected events in energy (0.3 – 0.7 keV for charge exchange, and 0.8 – 2.0 keV for stellar photosphere emission), we found that we best removed the instrumental background signal while preserving the flux from astronomical sources. Even after energy filtering, a low level of background counts was found throughout the *Chandra* field of view (FOV). The average number of counts per pixel across the array was < 1, necessitating signal analysis using small-number, Poisson statistics. Smoothing out the background using a very large, 30 x 30 - Gaussian footprint produced a map which shows structure across the array similar to that expected from ROSAT 1/4 and 3/4 keV maps of the sky around (R.A.=283.60^o, DEC=-20.15^o), arguing that the dominant background contribution in the data is from the sky background.

As the ACIS-S3 FOV was tracking the sky at sidereal rates, stellar objects were fixed in pixel position, while Pluto slowly moved, at a rate of ~3" (or 6 ACIS-S pix)/hr, with a total track length of ~28 pixels during our observations. Creating images of our data in sky centered and Pluto-centered coordinates, we distinguished a number of stellar sources from the background. While the list of detected sources was only a small subset of the stars known to be in the field (Pluto was within 7° of the galactic plane on 24 February 2014), enough (6) were detected to register the field and determine the effective beamwidth during the observations. Using these we found that a 5.5-pixel-radius circle contains > 90% of the point sources flux for objects registering 10 to 100 counts total. Taking the 90% footprint and placing it over the nominal location of Pluto in the Plutocentric *Chandra* image, we found a total of 2.0 cts in the 0.3 – 0.6 keV energy range. Placing the same footprint at 1000 locations gridded around Pluto in the same image, we found an average of 0.292 ± 0.522 (1σ) background cts. We could thus claim a net Pluto signal of 1.71 ± 0.522 (1σ) cts from the Feb 2014 *Chandra* observations and marginally significant above zero. From this marginal detection, and using previous *Chandra* observations of JFC comets [7-14] for calibration, NH SWAP's measurement of the SW flux, and the value of 33.2 AU for the Pluto-*Chandra* distance on 24 Feb 2014 we related this "detection" to the product of the SW flux and neutral gas production rate from Pluto and found $Q_{gas} \leq 1.5\text{x}10^{28}$ mol/sec. This upper limit was useful, in that it roughly bounded from above the pre-encounter estimated Q_{gas} rates of $2\text{x}10^{27}$ and $5\text{x}10^{27}$ mol/sec produced by global atmospheric models of Pluto [18,19].

26 Jul – 03 Aug 2015 Measurements: Using the positive results of these 35 ksec "seed" observations, we contacted the *Chandra* project and requested additional observing time during the New Horizons Pluto encounter. We were generously awarded another 145 ksec of observatory time to study Pluto using the same methodology and the NH *in situ* measurement of the Plutonian SW to determine robustly if our marginal detection was real. Due to Chandra pointing restrictions, we could not begin observing until 26 July 2015, but were then able to obtain another 142 ksec of on-target observations from 26 Jul – 03 Aug 2015. We detected another 6 cts at 0.3–0.6 keV, on top of a background of 1.20 ± 1.16 cts. **Added to the 2014 results, we find a total Pluto x-ray signal of 6.55 ± 1.28 cts, a total count rate of $3.7 \text{ x } 10^{-5}$ cps, and a 5.4σ detection of Pluto** in an 11x11 pixel (5.5"x5.5") box centered on its ephemeris position.

Where are the observed Plutonian x-rays coming from? X-rays are commonly detected in the solar system from (1) auroral SW precipitation, (2) charge exchange or (3) scattering of solar x-rays. However none of these physical explanations is satisfactory for Pluto: (1) Pluto is thought to have no intrinsic magnetic field and thus no appreciable aurora is expected. (2) X-ray emission via charge exchange between highly stripped hydrogenic and heliogenic minor ions in the SW and neutral gas species in comets and planetary atmospheres has been known to exist since the 1st ROSAT observations of comet Hyakutake in 1996 [14] and has been detected from the short period JFC comet population for all objects within a few AU of the Sun with loss/escape rate $Q_{gas} > 1 \text{ x } 10^{27}$ mol/sec. Following the models of Cravens [15], we expect the X-ray emission rate to trend linearly as the objects' Q_{gas}. Results from the NH ALICE UV occultations and NH PEPSSI and SWAP SW bowshock measurements for the neutral atmosphere escape rate find $Q_{gas} < 1 \text{ x } 10^{26}$ mol/sec [6,16,17], as compared to the $Q_{gas} \sim 1.1\text{x}10^{28}$ mol/sec we find assuming charge exchange dominated emission and our $3.7 \text{ x } 10^{-5}$ cps Chandra Pluto count rate. (3) While the 0.3 – 0.6 keV photons are in the proper energy range to be due to scattering by the N_2, CH_4, or H_2O on the surface of Pluto and Charon, extrapolating Dennerl's *Chandra* ACIS-I observations of Martian solar x-ray scattering [18] to Pluto produces a count rate estimate ~3 orders of magnitude lower than measured.

Could resonant scattering by abundant nm-sized dust grains in Pluto's enveloping haze [1,6] be the cause of Pluto's high observed x-ray count rate?

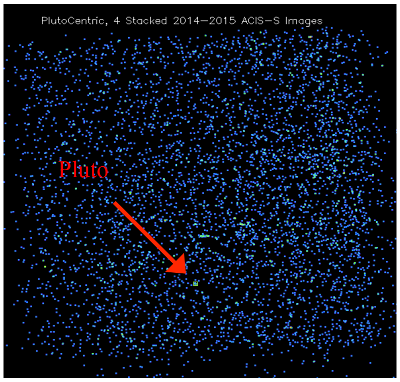

Figure 1 – Results of our *Chandra* ACIS-S 2014-2015 Pluto observations. The 0.3 - 0.6 keV events from all 4 epochs (177 ksec total on-target time) have been co-added in a Plutocentric frame moving with the planet.

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