LIMITS ON PLUTO'S ATMOSPHERIC ESCAPE RATE FROM CHARGE EXCHANGE X-RAYS. C. M. Lisse[1], R. L. McNutt, Jr[1], A. S. Stern[2], T. E. Cravens[3], M. E. Hill[1], D. F. Strobel[4], X. Zhu[1], H. A. Elliott[5], A. Chutjian[6], H. A. Weaver[1], D. J. McComas[5], S. J. Wolk[7], and L. A. Young[2]. [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, [2]Southwest Research Institute, Boulder, CO, USA, [3]University of Kansas, Lawrence, KS, USA, [4]Johns Hopkins University, Baltimore, MD, USA, [5]Southwest Research Institute, San Antonio, TX, USA, [6]Jet Propulsion Laboratory, Pasadena, CA, USA, and [7]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA.

Introduction: Pluto, the first discovered Kuiper Belt Object (KBO), and one of the largest KBOs currently known, lies at the outer edges of our solar system and is the target of a 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 models of its atmosphere [4, 5] formulate a majority N_2 atmosphere with scale height ~3000 km and free escape of ~10^{28} mol/sec [6]. This is very similar to the physical situation of a JFC comet observed by Chandra at 1 AU [7-13], .In many ways Pluto and its atmosphere may be behaving like a very large comet [14-16], which is quite consistent with the physical picture of KBOs as the parents of the inner system Centaurs and Jupiter Family Comets.

X-ray emission created via charge exchange between highly stripped hydrogenic and heliogenic minor ions in the solar wind and neutral gas species in comets and planetary atmospheres has been known to exist since the ROSAT observations of comet Hyakutake in 1996 [17]. Now known to be a ubiquitous property of all comets, detectable levels of X-ray emission have been detected from the short period JFC comet population for objects with gas production (and loss/escape rate) Q_{gas} > 1 x 10^{27} molecules/sec by the ROSAT, BeppoSax, ASCA, CHIPS, Suzaku, Chandra, and XMM x-ray observatories. Following the model of Cravens, we expect the X-ray emission rate to trend linearly with the comet's gas production rate and solar wind fluence. Thus, by applying the knowledge gained by studying cometary X-ray emission, Chandra Advanced CCD Imaging Spectrometer (ACIS)-S photometric imaging of X-rays produced by charge exchange between the solar wind and Pluto's atmosphere can address both the run of atmospheric density with distance from Pluto and the interaction of the solar wind with the extended Plutonian atmosphere. Pinning down the atmosphere's extent and exact amount of free molecular escape would corroborate the exospheric emission measurements of the NH ALICE instrument, while determining the x-ray luminosity would help the NH PEPSSI instrument determine the solar wind particle environment at Pluto, and the ultimate fate of escaping gas, i.e., by charge exchange with the solar wind or photoionization from solar UV radiation.

Given that most models of Pluto's atmosphere derive a near-body thick exobase surmounted by a gravitationally unbound layer losing ~10^{27} to 10^{28} mol/sec of N_2 and CH_4, we felt that it could be possible to detect X-ray emission created by charge exchange from Pluto. While the JFC comets detected in the X-ray were all within 3 to 4 AU of the Sun and Pluto resides at some 30 to 40 AU, the solar wind flux decreases as $1/r^2$ and the projected Chandra pixel size increases as r^2, meaning that a neutral's lifetime vs charge exchange ~ r^2 and roughly the same number of total emitting centers would be in each Chandra pixel for Pluto as for a JFC comet, i.e., while the solar wind strength decreases by ~$1/33^2$, Chandra's 0.5"pixels are 33^2 larger, about ~12,000 km on a side at Pluto's distance from the Sun. The neutral gas escaping from Pluto should extend ~33 times farther out from the planet as compared to the gas emitted by a comet nucleus at 1 AU from the Sun, and the total amount of Pluto charge-exchange driven X-ray emission should be about the same as for a medium bright JFC comet (e.g., 2P/Encke observed by Chandra in 2003, Lisse et al. 2005; or 9P/Tempel 1 observed by Chandra in 2005. Based on our previous JFC comet observations, we expected a total Chandra count rate for Pluto on the order of 1 x 10^{-3} cps (1/Delta scaling) or 3 x 10^{-5} (1/Delta^2 scaling). 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 possibly dominate the observed X-ray signal.

We applied for and received 35 ksec of Chandra time to to image photometrically the system during the observatory's Cycle 15 of Guest Observer (GO) observations, spanning November 2013 to November 2014. Given the Chandra visibility window constrains for the Pluto system, the first viable observations were possible starting mid-February 2014. To maximize the potential signal from the Chandra observations versus the instrumental and sky backgrounds, we worked to schedule the Chandra Pluto observations at a time when the variable solar wind fluence as extrapolated to Pluto's location would be near its maximum. We used the solar wind trends measured by the NH Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) and NH Solar Wind Around Pluto (SWAP) instruments, which were ~4 AU upstream of Pluto at the time of our observations and had been monitoring the solar wind for almost a eyar previously while NH was in its "hibernation mode." At the time of the observations we had received down-loaded NH data only through Oct 2013, The need to extrapolate the solar wind cnditions forward in time to late February 2014 introduced significant uncertainties in the extrapolation. Subsequently data through this period has been dowmnlinked, which allows us to recreate solar wind conditions during our observation.)

Observations: Chandra ACIS-S spectral imaging observations of the Pluto system were obtained under Chandra program #15699 using a single, spacecraft, 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. Specifically, the Chandra sweet spot aim point was placed at RA=18 54 24.12, DEC=-20 09 00 on the sky. Chandra did not track with Pluto, but instead tracked sky-fixed targets at the nominal sidereal rate. The instrument was operated in VF event-detection mode, and a total of 8700 counts were detected on the S3 array during 35 ksec of observing. By filtering these events in energy, restricting them to photons between 0.3 and 2.0 keV (the energy range for chagre-exchange photons), we find that we best remove 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 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 pixels)/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^{o} of the galactic plane on 24 February 2014), enough (6) were detected to register the field and determine the effective beamwidth during the observations.

Results: We find a good match with detected background pt sources in our field and known RASS sources. Using these we find 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 find a total of 4 counts. Placing the same footprint at 1000 randomly chosen locations in the same image, we find an average of 2 ± 2 (2s) counts. Allowing for variations in the sky background, when we perform the same experiment with locations forced to be within 200 pixels of the nominal Pluto position, we find an average signal of 2.6 ± 2.0 counts. A more sophisticated Bayesian analysis is consistent with these results, as is injecting an artificial 2 count/ sec source into the Chandra field and recovering it using our aperture photometry method.

We can claim at best a detection of Pluto at the 1.4 ± 2.0 level, which is not statistically significant above zero. From this non/marginal detection, we find that the observations are in the unresolved limit and that Pluto has a very tightly confined, non-power-law run of atmospheric neutral density with distance from its barycenter, unlike that of a comet where the atmospheric number density trends as 1/distance^{2} out past 10^{5} km. (2) Using previous Chandra observations of JFC comets as calibrations, and with knowledge of the Pluto-Chandra distance we can relate the "detection" and 3σ upper limit X-ray count rates to the product of the solar wind flux and neutral gas production rate from Pluto. If we use a value of 2 counts/35 ksec, we find $Q_{gas} < 1.5 \times 10^{28}$ mol/sec. This upper limit is useful, in that it bounds the estimated Q_{gas} rates of 2×10^{27} and 3×10^{27} mol/sec produced by global atmospheric models of Pluto [18,19].

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