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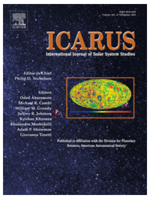

The puzzling detection of x-rays from Pluto by *Chandra*

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ABSTRACT

Using *Chandra ACIS-S*, we have obtained low-resolution imaging X-ray spectrophotometry of the Pluto system in support of the New Horizons flyby on 14 July 2015. Observations were obtained in a trial "seed" campaign conducted in one visit on 24 Feb 2014, and a follow-up campaign conducted soon after the New Horizons flyby that consisted of 3 visits spanning 26 Jul to 03 Aug 2015. In a total of 174 ksec of on-target time, in the 0.31 to 0.60 keV passband, we measured 8 total photons in a co-moving 11×11 pixel^2 box (the 90% flux aperture determined by observations of fixed background sources in the field) measuring $\sim 121{,}000 \times 121{,}000$ km^2 (or $\sim 100 \times 100$ R_{Pluto}) at Pluto. No photons were detected from 0.60 to 1.0 keV in this box during the same exposures. Allowing for background, we find a net signal of 6.8 counts and a statistical noise level of 1.2 counts, for a detection of Pluto in this passband at $> 99.95\%$ confidence. The Pluto photons do not have the spectral shape of the background, are coincident with a 90% flux aperture co-moving with Pluto, and are not confused with any background source, so we consider them as sourced from the Pluto system. The mean 0.31 - 0.60 keV X-ray power from Pluto is 200 $^{+200}/_{-100}$ MW, in the middle range of X-ray power levels seen for other known Solar System emission sources: auroral precipitation, solar X-ray scattering, and charge exchange (CXE) between solar wind (SW) ions and atmospheric neutrals. We eliminate auroral effects as a source, as Pluto has no known magnetic field and the New Horizons *Alice* UV spectrometer detected no airglow from Pluto during the flyby. Nano-scale atmospheric haze particles could lead to enhanced resonant scattering of solar X-rays from Pluto, but the energy signature of the detected photons does not match the solar spectrum and estimates of

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Pluto's scattered X-ray emission are 2 to 3 orders of magnitude below the $3.9 \pm 0.7 \times 10^{-5}$ cps found in our observations. Charge-exchange-driven emission from hydrogenic and heliogenic SW carbon, nitrogen, and oxygen (CNO) ions can produce the energy signature seen, and the 6×10^{25} neutral gas escape rate from Pluto deduced from New Horizons' data (Gladstone et al. 2016) can support the $\sim 3.0\ ^{+3.0/}{}_{-1.5} \times 10^{24}$ X-ray photons/s emission rate required by our observations. Using the solar wind proton density and speed measured by the Solar Wind Around Pluto (SWAP) instrument in the vicinity of Pluto at the time of the photon emissions, we find a factor of 40 $^{+40/}{}_{-20}$ lower SW minor ions flowing planarly into an 11×11 pixel^2, 90% flux box centered on Pluto than are needed to support the observed emission rate. Hence, the SW must be somehow significantly focused and enhanced within 60,000 km (projected) of Pluto for this mechanism to work.

1. 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 (Stern, 2008, Stern et al. 2015). Pluto is known to have an atmosphere which changes size and density with its seasons (Elliot et al. 1989, 2003, McNutt et al. 1989, Strobel et al. 2008). Preliminary simulation results of its atmosphere from the flyby revealed a majority N_2 atmosphere with a condensed exobase of ~1000 km height and a low escape rate of $< 7 \times 10^{25}$ mol/s (Stern et al. 2015, Gladstone et al. 2016). 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 Astronomical Units (AU) from the Sun, although the presence of a long extended plasma tail streaming downstream from Pluto (McComas et al. 2016) may have aspects of the comet case at 1 AU (Bodewits et al. 2007, 2012; Christian et al. 2010; Dennerl et al. 1997, 2012; Lisse et al. 1996, 2001, 2005, 2007, 2013; Wegmann et al. 2004, Wegmann & Dennerl, 2005; Wolk et al. 2009).

Given that most pre-encounter models of Pluto's atmosphere had predicted it to be much more extended, with an estimated loss rate to space of $\sim 10^{27}$ to 10^{28} mol/s of N_2 and CH_4 (similar to the typical H_2O loss rates for Jupiter Family Comets (JFC) comets at 1 AU; Bagenal & McNutt, 1989, Bagenal et al. 1997, Delamere & Bagenal, 2004, Tian & Toon, 2005, Strobel, 2008, Zhu et al. 2014, Tucker et al. 2012, 2015), we attempted to detect X-ray emission created by SW-neutral gas charge exchange interactions in the low density neutral gas surrounding Pluto similar to those found in other Solar System environments (Cravens, 1997, Lisse et al. 2001, Dennerl 2002, Wargelin et al. 2004, 2014; Dennerl, 2010, Collier et al. 2014). Even though the solar illumination and the SW flux both decrease as $1/r^2$, causing a near-Pluto neutral molecule's lifetime against photionization and charge exchange to be measured in years rather than days (Bagenal et al. 2015), the projected *Chandra* pixel size increases as r^2. Hence, roughly the same number of total emitting X-ray centers should be in each *Chandra* projected $12{,}000 \times 12{,}000$ 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 (Lisse et al. 2005) or 9P/Tempel 1 observed by *Chandra* in 2005 (Lisse et al. 2007)). Based on our previous JFC comet X-ray detections, and an estimated neutral gas escape rate $Q_{gas} \sim 3 \times 10^{27}$ mol/s, we expected a total *Chandra* count rate for Pluto on the order of 3×10^{-5} cps. With an estimated chip background rate of $\sim 1 \times 10^{-6}$ cps, the major concern with observing Pluto was that any sky or particle backgrounds could dominate the observed X-ray signal.

In late 2013 we received 35 ksec (~10 h) of *Chandra* time to image the system spectrophotometrically. 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 flux as extrapolated from New Horizons to Pluto's location would be near its maximum. We used the SW trends measured by the NH Solar Wind Around Pluto (SWAP) instrument (McComas et al. 2008), which was ~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.

2. Results and analysis

2.1. 24 Feb 2014 observations

Spectral imaging observations of the Pluto system using the *Chandra* Advanced CCD Imaging Spectrometer (ACIS) - S-array (ACIS-S) were obtained under *Chandra* program #15,699 using a single telescope sky pointing from 24 Feb 2014 02:02:51 to 12:17:15 UTC (Tables 1 and 2). 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 the motion of Pluto on the sky, 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 chip during 35 ksec of observing. By filtering the detected events in energy (0.31 to 0.60 keV for charge exchange, and 0.8 to 2.0 keV for stellar photosphere emission), we found that we best removed the instrumental background signal while preserving the flux from astronomical sources. (The carbon K-shell edge is at 280 eV, close to the *Chandra* background peak spanning 250 ± 50 eV, making Pluto CV photons hard to distinguish from ACIS-S background photons. For this reason we have chosen to exclude X-ray photons below 310 eV range in this study.) 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, 30×30 pixel^2 Gaussian footprint produced a map which shows structure across the array similar to that expected from Röntgensatellit (ROSAT) 1/4 and 3/4 keV maps of the sky around (R.A.=283.60°, DEC=−20.15°). This argues that the dominant low energy X-ray background contribution in the data is from the sky background, consistent with other studies (Slavin et al. 2013, Wargelin et al. 2014).

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 ~3.8″ (or 7.5 ACIS-S pixels) per hour, with a total track length of ~72 pixels during our observations. Creating

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