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Hot Topics in the Solar System—Chandra Observations

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Abstract. In this short paper, I summarize *Chandra* observations of various objects in the Solar System. In addition to the Moon and several comets, *Chandra* has observed all the planets between Venus and Uranus. With one exception, all have been clearly detected.

1. Introduction

X–rays are generally associated with extremely high temperature phenomena of at least 1 million K, up to and beyond 100 million K. Yet, in the Solar System we detect X–rays from objects with typical temperatures well below 1000 K. We observe X–rays from a wide variety of phenomena and under a broad range of conditions. Key production mechanisms include: Fluorescence – in which solar radiation directly excites a neutral atom or molecule and charge exchange – by which an electron from a low density neutral is passed to a highly ionized species in the Solar wind. Other production mechanisms include photon elastic scattering, Electron–ion bremsstrahlung and heavy ion precipitation through a magnetosphere. An exciting aspect of this research is that several of these processes involve the production of new X–ray photons in addition to those produced in the Solar corona. The *Chandra* X–ray Observatory (CXO) has observed all the planets in the Solar System between Venus and Uranus and well as the Moon and nearly half a dozen comets. All of the listed production mechanism have been found to play a role.

2. The Moon

The Moon was actually the first target in the search for X–rays outside of the Earth and the Sun. A sounding rocket failed to detect scattered solar X–rays from the Moon between 1.5 and 6 keV (Giaconni et al. 1962). The on-board geiger counter did discover Sco X-1 so the mission was not a complete loss. X–rays were detected from the Moon by Apollo using a variety of experiments. ROSAT became the first telescope to image the Moon in X–rays. This observation was proof of the cosmological nature of the X-ray background as it was blocked by the dark side of the Moon. Schmitt et al. (1991) argued that the Moon's X–ray luminosity does arise from scattering of solar X–rays. They also detected faint X–ray emission from the dark portion of the Moon, they attribute this emission to solar wind electrons striking the lunar surface.

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Spectra from recent *Chandra* observations indicate that the emission from the dark side of the Moon may actually be geocoronal emission occurring between the Earth and the Moon as solar wind ions capture electrons from hydrogen atoms in the extreme upper reaches of the Earth's atmosphere (Wargelin et al. 2003 *in prep.*). The *Chandra* observations of the illuminated portion of the Moon detect X–ray emission lines from oxygen, magnesium, aluminum and silicon. The X–rays are now thought to be produced by fluorescence when solar X–rays bombard the lunar surface.

3. Comets

Comets are arguably the most surprising X–ray sources in space. Their X–ray emission was discovered by ROSAT during the apparition of Hyakutake in 1996 (Lisse et al. 1996). With a luminosity of about $10^{15} erg/sec$ Hyakutake was the third brightest X–ray source in the solar system after the Sun and Jupiter. Between 1996 and 1999 about a dozen comets were observed with ROSAT, ASCA, RXTE, EUVE and BeppoSaX having X–ray luminosities reaching that of Jupiter. Much as in the case of the Moon, the low spectral resolution of this previous generation of X–ray instruments left the production mechanism uncertain. It was clear a very efficient mechanism was needed.

Chandra observed comet C/Linear 1999 S4 in a series of eight 1 ks snapshots on July 14, 2000 (Lisse et al. 2001). The strong oxygen feature in the spectrum produced by the Advanced CCD Imaging Spectrometer (ACIS) immediately ruled out all models except charge exchange as the sole source of the X–ray production. The best fit models to the data include charge exchange lines overlying a soft thermal spectrum.

A unique aspect of the C/Linear 1999 S4 encounter was that the comet broke up during perihelion passage. The somewhat serendipitous observation of the post breakup comet still showed detectable levels of oxygen emission related to charge exchange. The X–ray emission dropped by about a factor of about 8 similar to the observed drop in both the gas and the dust production (Schleicher & Eberhardy 2000). Thus, one cannot separate the contributions of the gas and the dust from this result.

Chandra has since observed several other comets including: 1) McNaught-Hartley (Krasnopolsky et al. 2002) which had 3 times the photons as C/Linear 1999 S4 and a nearly identical spectrum. 2) C/Linear 2000 WM1 (Lisse PI 2001) which obtained a dispersed X–ray spectrum of a comet. 3) Ikeya-Zhang (Dennerl et al. – *in prep.*) was twice as bright as McNaught-Hartley and 4) an HRC observation of C/Linear 2001 A2 (Vestrand PI 2000).

The observations of Ikeya-Zhang were designed to give us insight to the morphology of a comet. The image clearly shows a "D" shape with the center of the "D" displaced about 50,000 km sunward of the cometary nucleus. While emission extends about 250,000 km transverse of the direction of the cometary motion and about 300,000 km toward the Sun, the emission falls to near zero within about 100,000 km in the anti-sun direction.

For all comets, the emission seems to track the solar wind at the location of the comet. The detected lines indicate the species in the wind while the luminosity scales with the wind flux. There seems to be a maximum X–ray radius of about 10^6 km which is set by the ionization length scale of H_2O. This combination leads to a maximum luminosity of about $10^{16} erg/sec$ set by the number of solar wind ions. A corollary to this is that comets around young stars, with mass loss rates which are many orders of magnitude greater than that of the sun, should have X–ray emission several orders of magnitude greater than solar system comets. In addition, young stars should have, perhaps, hundreds of comets proximate to them at any given time.

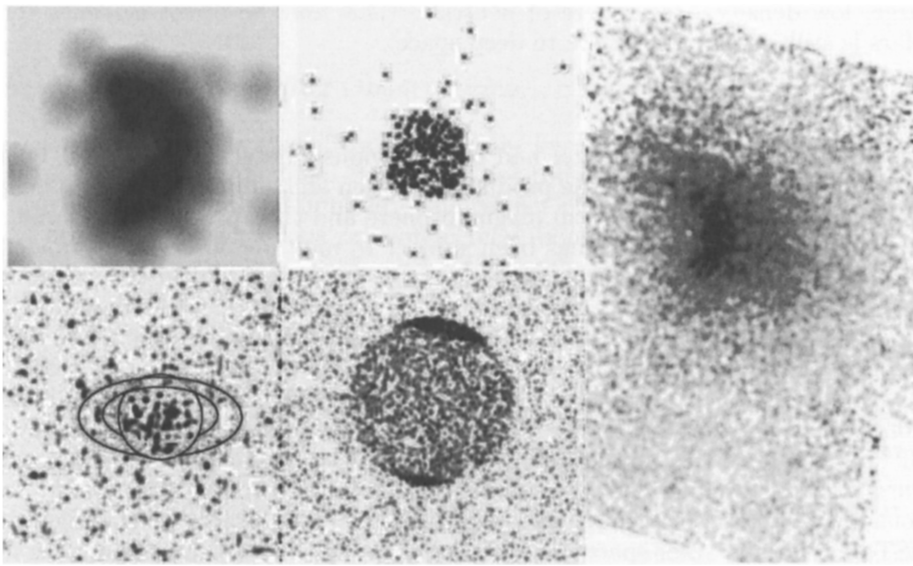

Figure 1. A rogues gallery of nearby X–ray sources. They are: (upper left) a Gaussian smoothed image of Venus. (upper-middle) Mars, (right) Comet Ikeya-Zhang - The small dot near the middle indicates the nucleus. This image is slightly smoothed. (lower-center) Jupiter. (lower-left) A preliminary view of Saturn with modest smoothing. References are given in the text.

4. The Planets

Most of the Solar System's planets have been observed by CXO. These observations are challenging due to the relative motion of the bodies and their optical brightness which can be beyond the design limit of the optical blocking filters of the ACIS.

4.1. Venus

Venus was observed by Dennerl et al. (2001) using both the ACIS-I array and the low energy transmission grating with the ACIS-S array. Lines of carbon, nitrogen and oxygen were clearly seen. The X–ray emission extends above the cloud tops and unlike the optical emission it is clearly limb brightened. The morphology, luminosity and spectra are consistent with fluorescent X–ray scattering of solar X–rays by atoms about 110 km above the surface.

4.2. Mars

Mars, undetected by ROSAT, was observed in July 2001 by CXO. Dennerl (2002) used the ACIS-I detector. Mars is similar to Venus in that oxygen was detected with a morphology, luminosity and energy spectrum consistent with fluorescence scattering of X–rays at 80 km above the Martian surface. Unlike Venus though, a weak X-ray signal was detected extending several radii beyond the planet. This may be the signature of change exchange between the solar wind and a large, low density, atmosphere of neutrals. This may be direct evidence that Mars is still losing atmosphere to deep space.

4.3. Jupiter

Unlike Mars and Venus, Jupiter had been previously detected in X–rays. Polar emission was thought to be the product of oxygen and sulfur ions from Io being transported through the Jovian magnetosphere and then precipitating through the auroral regions. Jupiter has been subject to multiple observing campaigns with CXO. The first campaign was part of the initial guaranteed time program in 1999. In these observations, most of the Jupiter data were compromised by optical loading on the ACIS which caused most of the X–rays which were detected on the spacecraft to be misinterpreted and not transmitted to the Earth.

An alternative observation was performed in 2000 using the High Resolution Camera (HRC). Gladstone et al. 2002 easily detected emission of about $10^{16} erg/sec$ from the entire surface of Jupiter with a strong concentration toward the poles. While the general surface emission is presumably from scattered Solar X–rays, the polar emission is poleward of the auroral regions imaged by HST and various other spacecraft. This means the the material responsible for this emission cannot be Io as previously thought and must emanate more than 30 R_{Jup} away. This leaves the Sun as the probable source of the ions which collide with the Jovian atmosphere near the poles. The polar emission is seen above both poles to pulse with a 45 minute cadence. A search for a 45 minute resonance in the observation or within Sun-Jupiter interaction has not found a suspected source for the periodicity.

Elsner et al. (2002) revisited the early ACIS observations. While the data from Jupiter itself was uninterpretable, they found X–ray emission from the moons Io and Europa. They believe this emission comes from bombardment of the satellites' surfaces by hydrogen, oxygen and sulfur in the Io plasma torus which itself is detectable at about 10% the total luminosity of Jupiter itself.

4.4. Saturn

Saturn was observed by CXO for the first time in April 2003 (Ness et al. – *in prep.*). Previously Ness & Schmitt (2000) had reported a ROSAT detection of 22 photons coincident with Saturn in a 5.3ks interval. Only 7.6 photons were expected. From this they derived a flux of about $2 \times 10^{-14} ergs/cm^2/sec$. In the *Chandra* observations, Ness et al. detect over 100 counts above the background. While the CXO observation puts the detection of Saturn on firm footing, the observed flux was 20% the flux expected based on the ROSAT result. Analysis of these data are ongoing but there is no evidence of polar concentration nor temporal variability in the signal from Saturn.

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4.5. Uranus and the Earth

Two other planets have also been observed by CXO. Earth was observed in 2003 by Gladstone, Elsner & Waite using the HRC. Following from their Jovian experience they hypothesize a particle source region near Earth's magnetopause and auroral entry of heavy solar wind ions due to high-latitude reconnection. A weak detection is seen in the publicly available data. Uranus was observed by Metzger in 2002. No source is obvious in the data. A similar null result was seen from the asteroid 1998 WT 24.

5. Recent & Upcoming Observations

To some it may seem that if each object has been observed once, then the contribution from CXO is done. But this is not the case. Most of the observations reported here are photon limited. One cannot clearly identify the multiple X–ray production mechanisms present in most bodies. None of the observations is able to take advantage of *Chandra's* full resolution due to these photon limitations. During *Chandra's* cycle 4, Jupiter was revisited by both HRC and by ACIS (using a mode specialized to overcome the optical light leak). There was also an unique observation of Titan as it passed only a few arc seconds from the Crab pulsar.

In the upcoming cycle 5, approved observations include a more detailed study of the Earth's north polar cusp, a two rotation period observation of Saturn coordinated with the first Cassini encounter, and the first attempt at cometary tomography as 2P/Encke is observed for an entire rotation period.

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