XMM-NEWTON SPECTROSCOPY OF JUPITER

G. Branduardi-Raymont [a]

[a]MSSL, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK

Two *XMM-Newton* observations of Jupiter were carried out in 2003 for 100 and 250 ks (or 3 and 7 planet rotations) respectively. X-ray images from the EPIC CCD cameras show prominent emission from the auroral regions in the 0.2−2.0 keV band: the spectra are well modelled by a combination of emission lines, including most prominently those of highly ionised oxygen (OVII and OVIII). In addition, and for the first time, *XMM-Newton* reveals the presence in both aurorae of a higher energy component (3−7 keV) which is well described by an electron bremsstrahlung spectrum. This component is found to be variable in flux and spectral shape during the Nov. 2003 observation, which corresponded to an extended period of intense solar activity. Emission from the equatorial regions of Jupiter's disk is also observed, with a spectrum consistent with that of solar X-rays scattered in the planet's upper atmosphere. Jupiter's X-rays are spectrally resolved with the RGS which clearly separates the prominent OVII contribution of the aurorae from the OVIII and FeXVII lines originating in the low-latitude disk regions of the planet.

1. Introduction

By analogy with the Earth's aurorae, the X-ray emission of Jupiter, first detected by the *Einstein* observatory [1], was expected to be due to bremsstrahlung by energetic electrons precipitating from the magnetosphere. However, the X-ray spectrum is softer (0.2−3 keV) and the fluxes larger than predicted from this mechanism. The alternative process is K-shell line emission from ions, mostly of oxygen, which charge exchange, are left in an excited state and then decay back to the ground state [2]. The ions were thought to originate in Jupiter's inner magnetosphere, where an abundance of sulphur and oxygen, associated with Io and its plasma torus, is expected [1].

ROSAT soft X-ray (0.1−2.0 keV) observations showed a spectrum much more consistent with recombination line emission than with bremsstrahlung [3,4]. They also revealed low-latitude 'disk' emission from Jupiter [5], and this too was attributed to charge exchange. However, the X-rays were brightest at the planet's limb corresponding to the bright visible limb, suggesting that a solar-driven mechanism may be at work [6]. Scattering of solar X-rays, both elastic (by atmospheric neutrals) and fluorescent (of carbon K-shell X-rays off methane molecules below the Jovian homopause), was proposed as a way to explain the disk emission [7].

The *Chandra* observatory has given us the clearest view yet of Jupiter's X-ray emission: HRC-I observations in Dec. 2000 and Feb. 2003 clearly resolve two bright, high-latitude sources associated with the aurorae, as well as low-latitude emission from the planet's disk [8,9]; magnetically the North X-ray hot spot maps to distances in excess of 30 Jovian radii, rather than to the inner magnetosphere and the Io plasma torus. Since in the outer magnetosphere ion fluxes are insufficient to explain the observed X-ray emission, another ion source (solar wind?) and/or acceleration mechanism are required. Strong 45 min quasi-periodic X-ray oscillations were also discovered using *Chandra* in the North auroral spot in Dec. 2000, without any correlated periodicity being found in solar wind data, or in energetic particle and plasma wave measurements [8]. The 2003 data from *Chandra* ACIS-S [9] show that the auroral X-ray spectrum is made up of oxygen line emission consistent with mostly fully stripped ions. Line emission at lower energies could be from sulphur and/or carbon. Rather than periodic oscillations, chaotic variability of the auroral X-ray emission was observed, with power peaks in the 20−70 min range. A promising mechanism which could explain this change in character of the variability, from organised to chaotic, is pulsed reconnection at the day-side magnetopause, as suggested by [10].

2. *XMM-Newton* observations

XMM-Newton observed Jupiter twice in 2003: between Apr. 28, 16:00 and Apr. 29: 22:00 UT (110 ks; see Fig. 1, from [11]) and between Nov.

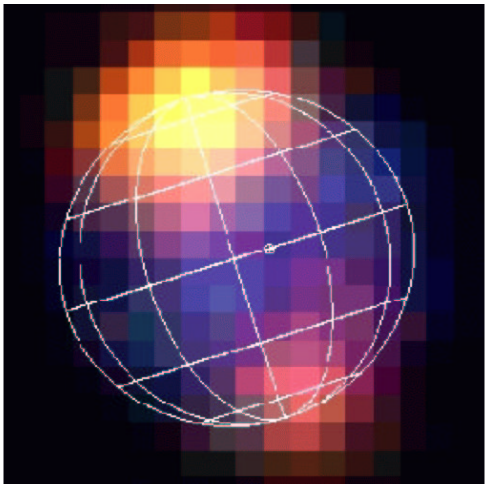

Figure 1. Smoothed *XMM-Newton* EPIC image of Jupiter (2.9" pixels), Apr. 2003. North is to the top, and East to the left. Colour code: Red: 0.2–0.5 keV; Green: 0.5–0.7 keV; Blue: 0.7–2.0 keV. The equatorial emission is clearly harder than that from the auroral regions. A graticule showing Jupiter orientation with 30^{o} intervals in latitude and longitude is overlaid. The circular mark indicates the sub-solar point; the sub-Earth point is at the centre of the graticule.

25, 23:00 and Nov. 29, 12:00 UT (245 ks, split over spacecraft orbits 0726 and 0727 [12,13]).

2.1. Temporal behaviour

Lightcurves from the Nov. 2003 observation (Fig. 2) resemble very closely those obtained the previous April [11]. The planet 10 hr rotation period is clearly seen in the auroral data, but not in the equatorial region. The North spot is brightest around CML (System III Central Meridian Longitude) = 180^{o}, like in the Dec. 2000 *Chandra* and Apr. 2003 *XMM-Newton* observations. A 40% increase in the equatorial flux between the first and the second spacecraft revolution is noticeable in Fig. 2, and is correlated with a similar increase in solar X-ray flux (see [14] for a detailed study of the temporal behaviour of the low-latitude disk emission, which appears to be controlled by the Sun). A search for periodic variability on short time-scales in the auroral X-rays leads to a null result (as for the Apr. 2003 *XMM-Newton* data). This supports the view that over time the character of the variability in the auroral X-ray emissions can change from well organised to chaotic.

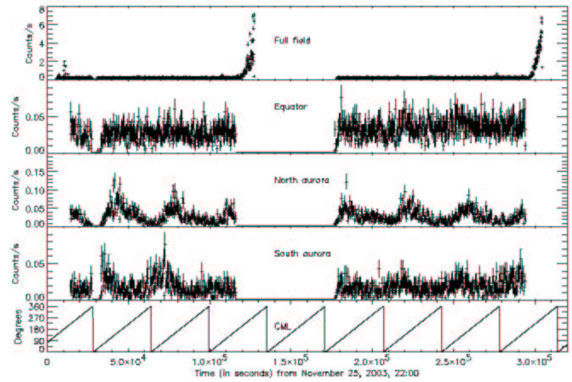

Figure 2. *XMM-Newton* Nov. 2003 Jupiter lightcurves. Middle three panels: Low-latitude disk and auroral emissions (0.2–2.0 keV, 300 s bins). Top panel: Lightcurve at energies >10 keV, showing periods of high background (excluded from the analysis). Bottom panel: System III Central Meridian Longitude (CML).

2.2. EPIC spectral images

The *XMM-Newton* observation of Jupiter in Apr. 2003 gave the first clear indication that the Jovian auroral and disk X-ray emissions have different spectra. Fig. 1 shows the planet's image colour-coded depending on X-ray energy: the equatorial disk emission is clearly harder that that of the aurorae. The auroral spectra can be modelled with a superposition of emission lines, including most prominently those of highly ionised oxygen (OVII and OVIII). Instead, Jupiter's low-latitude X-ray emission has a spectrum consistent with that of solar X-rays scattered in the planet's upper atmosphere [11]. These results are strengthened by the Nov. 2003 observation.

Figs. 3 shows the combined EPIC-pn [15] and -MOS [16] CCD images in narrow spectral bands corresponding to the OVII, OVIII, FeXVII and MgXI lines detected in Jupiter's spectra: OVII emission is concentrated mostly in the North and (more weakly) the South auroral spots, OVIII extends to lower latitudes, while FeXVII and MgXI display a rather uniform distribution over the planet's disk, consistent with an origin from scat-

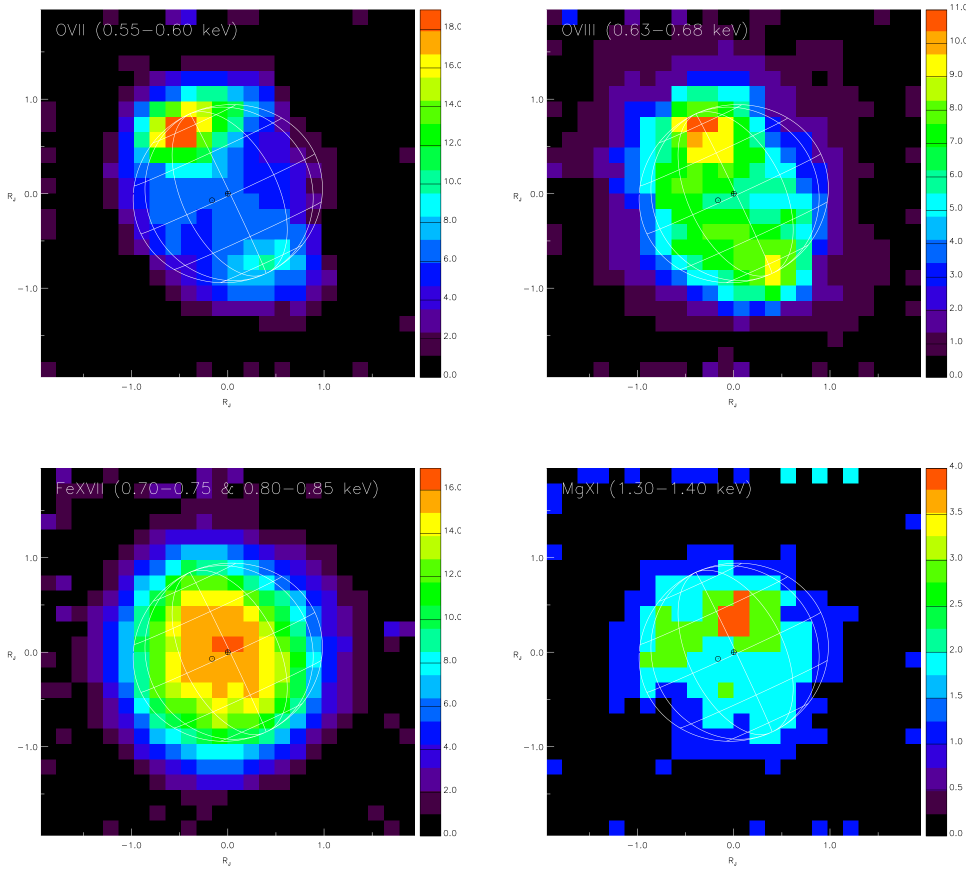

Figure 3. Smoothed *XMM-Newton* EPIC images of Jupiter in narrow spectral bands. From top left, clockwise: OVII, OVIII, MgXI, FeXVII. The colour scale bar is in units of EPIC counts.

tered solar X-rays.

Although most of the X-ray emission of Jupiter is confined to the 0.2−2 keV band, a search at higher energies has produced very interesting results. Fig. 4 (right) is an image of Jupiter in the 3−10 keV band, showing the presence of higher energy emission from the auroral spots, but not from the planet's disk.

2.3. EPIC spectra

EPIC CCD spectra of Jupiter's auroral zones and low-latitude disk emission were extracted using the regions outlined in Fig. 4; the spectral 'mixing' (due to the *XMM-Newton* Point Spread Function) was corrected for by subtracting appropriate fractions of disk and auroral emissions from the aurorae and the disk spectra respectively. Fig. 5 compares the resulting spectra of the North and South auroral spots and the disk for the Nov. 2003 observation.

As first pointed out by [11], there are clear differences in the shape of the spectra, with the auroral emission peaking at lower energy (0.5−0.6 keV) than the disk (0.7−0.8 keV). Emission features in the range 1−2 keV are visible in all the spectra, but are stronger in the disk [13]. The presence of a high energy component in the spectra of the aurorae is very evident, with a substantial excess relative to the disk emission extending to 7 keV. Variability in the auroral spectra is also observed (Fig. 6): the high energy part of the spectra varies between the two Nov. 2003 *XMM-Newton* revolutions, and changes are also observed at low energies.

2.4. EPIC spectral fits

A collisional plasma model (`mekal` in XSPEC) with temperature $kT = 0.46 \pm 0.03$ keV is a good

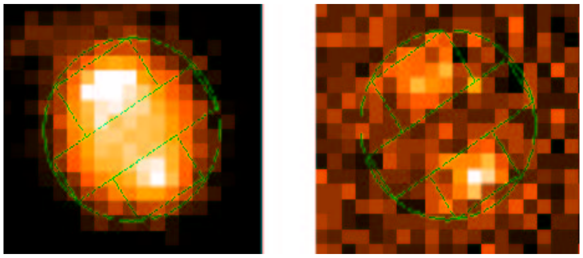

Figure 4. Jupiter's images from the combined *XMM-Newton* EPIC cameras data (∼1.4' side; left: 0.2−2 keV band; right: 3−10 keV). Superposed are the regions used to extract auroral and low-latitude disk lightcurves and spectra.

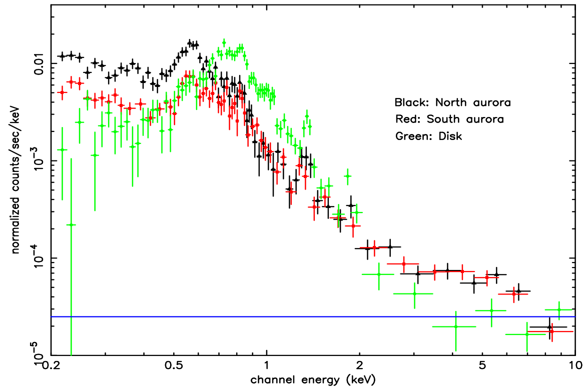

Figure 5. Combined EPIC spectra of the North (black) and South (red) aurorae, and of the low-latitude disk (green) spectrum. The horizontal blue line shows the estimated level of the EPIC particle background.

representation of the low-latitude disk spectrum, after including additional MgXI and SiXIII emission (at 1.35 and 1.86 keV respectively, likely consequences of enhanced solar activity) and a small contribution of OVII (0.57 keV) and OVIII (0.65 keV), both residual auroral contamination [12,13].

The auroral spectra are well fitted by a model comprising two thermal bremsstrahlung continua and four gaussian emission lines, at 0.32 keV (C and/or S), 0.57 (OVII), 0.69 (OVII and FeXVII) and 0.83 keV (Fe XVII) for rev. 0726; in rev. 0727 and in Apr. 2003 the lowest energy line is not present but one is needed at 1.35 keV (MgXI, probably residual contamination from scattered solar X-rays). The bremsstrahlung continua reflect the presence of two distinct components dominating at the low and high energy end of the spectra respectively. The temperature of the low energy component is fairly stable, ranging between 0.1 and 0.3 keV, and is practically the same for both aurorae. For the higher energy component, the rev. 0726 spectra require a much higher bremsstrahlung temperature than those from the two other epochs. Rather than measuring a physical change in temperature, this simply indicates that the spectral slope was much flatter in rev. 0726. The spectrum and its best fit for the North aurora from the Nov. 2003, rev. 0726, are shown in Fig. 7.

Fig. 8 displays the high energy continuum model components fitted to the Nov. 2003 auroral data and compares them with the predictions of [17] for bremsstrahlung emissions by electrons of energies between 10 and 100 keV. The bremsstrahlung fit of rev. 0727 lies remarkably close to the predicted spectrum for both the North and South aurorae. The models for rev. 0726, however, suggest a very different electron distribution for both aurorae.

2.5. RGS spectrum

Fig. 9 shows the soft X-ray RGS spectrum of Jupiter obtained by coadding the RGS1 and 2 data (first order only) from both *XMM-Newton* revolutions in Nov. 2003: the image is colour-coded according to the detected flux, and displays the spatial distribution of the emission in the cross dispersion direction (y axis) versus X-ray wavelength. The RGS clearly separates the emission lines of OVII (21.6−22.1 Å, or 0.56−0.57 keV), OVIII (19.0 Å, or 0.65 keV) and FeXVII (15.0 and ∼17.0 Å, or ∼0.73 and 0.83 keV). The RGS spectrum also shows evidence for the different spatial extension of the line emitting regions, in agreement with the EPIC spectral mapping of Fig. 3: OVII photons are spatially well separated into the two aurorae, while the other lines are filling in the low latitude/cross dispersion range.

A fit to the RGS spectrum, including both disk and charge exchange line emission components, is shown in Fig. 10: higher order transitions of OVII and OVIII are identified, and the Fe XVII doublets and OVII triplet are clearly separated.

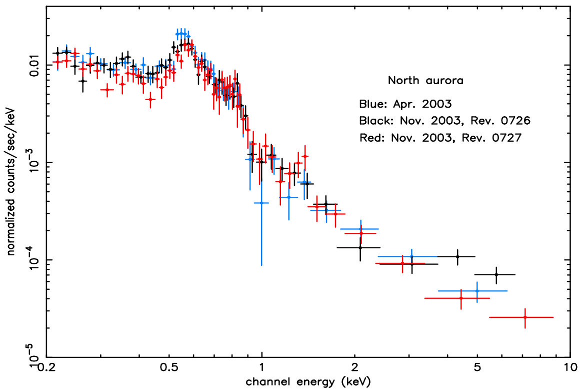

Figure 6. Combined EPIC spectra of the North aurora for the two separate *XMM-Newton* revolutions, 0726 (black) and 0727 (red), in Nov. 2003, and for the Apr. 2003 observation (blue).

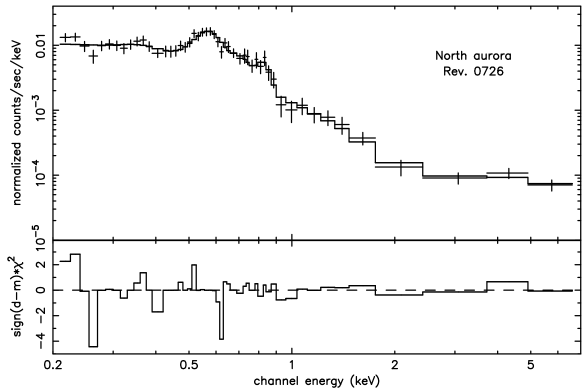

Figure 7. *XMM-Newton* EPIC spectrum of Jupiter's North aurora from the Nov. 2003, rev. 0726 observation, and best fit (see text for details).

3. Discussion and Conclusions

XMM-Newton observations of Jupiter in Apr. and Nov. 2003 convincingly demonstrate that the planet's auroral and low-latitude disk X-ray emissions are different in spectral shape and origin. Jupiter's disk emission is most likely due to elastic scattering and carbon K-shell fluorescence of solar X-rays. The Jovian auroral soft X-rays ($<$ 2 keV) are most likely due to charge exchange by energetic ions from the outer magnetosphere, or solar wind, or both. For the first time a higher energy component in the auroral spectra has been identified, and has been found to be variable over timescales of days: its spectral shape is consistent with that predicted from bremsstrahlung of energetic electrons precipitating from the magnetosphere. The variability observed in its flux and spectrum is likely to be linked to changes in the energy distribution of the electrons producing it and may be related to the particular period of intense solar activity reported in Oct. - Nov. 2003 by a number of spacecraft measurements.

Looking towards future X-ray observatory opportunities (which is really the aim of this workshop), the complex spectral mixing of Jupiter's X-ray emissions will require further enhancements in spectral resolution and especially in collecting area if are to acquire data of higher statistical quality than presently achievable with *XMM-Newton*. Planetary and cometary (i.e. moving target) X-ray observations, which are now popular, will impose considerations of field of view size and observing strategies, if too frequent spacecraft re-pointing is to be avoided. Ideally, small X-ray imaging spectrometers placed on-board planetary missions could provide high quality *in situ* observations, directly comparable with particle and other electromagnetic measurements from instruments in the same payload.

Acknowledgments

This work is based on observations obtained with *XMM-Newton*, an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA).

REFERENCES

1. Metzger, A. E., Luthey, J. L., Gilman, D. A. et al. 1983, J. Geophys. Res., 88, 7731
2. Bhardwaj, A. & Gladstone, G. R. 2000, Rev. Geophys., 38, 295
3. Waite, J. H., Jr., Bagenal, F., Seward, F. et al. 1994, J. Geophys. Res., 99, 14799
4. Cravens, T. E., Howell, E., Waite, J. H., Jr., & Gladstone, G. R. 1995, J. Geophys. Res., 100, 17153
5. Waite, J. H., Jr., Gladstone, G. R., Lewis, W. S. et al. 1997, Sci, 276, 104
6. Gladstone, G. R., Waite, J. H., Jr. & Lewis, W. S. 1998, J. Geophys. Res., 103, 20083

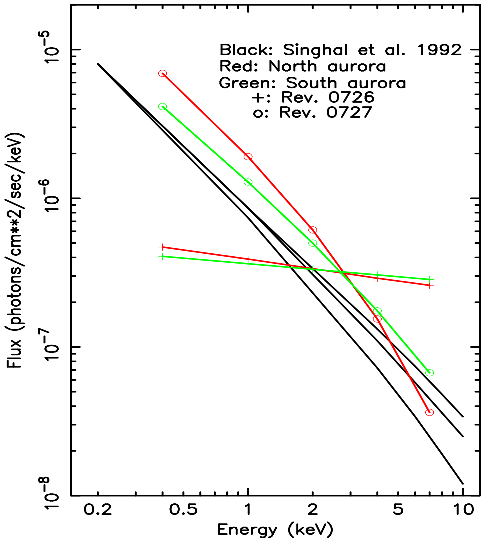

Figure 8. High energy model components fitted to the Nov. 2003 auroral data, compared with bremsstrahlung X-ray flux predictions by [17] for three characteristic electron energies (10, 30 and 100 keV, from bottom to top curve).

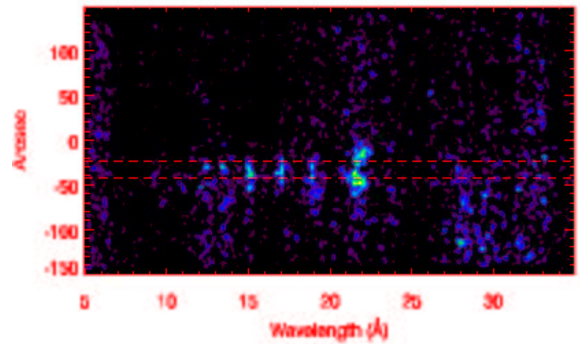

Figure 9. RGS spectrum of Jupiter from the combined RGS1 and 2 datasets of both *XMM-Newton* revolutions in Nov. 2003 (y axis = cross dispersion direction). The two dashed horizontal lines mark the location of Jupiter's aurorae (the planet's N−S axis was essentially perpendicular to the RGS dispersion direction).

7. Maurellis, A. N., Cravens, T. E., Gladstone, G. R. et al. 2000, Geophys. Res. Lett., 27, 1339
8. Gladstone, G. R., Waite, J. H., Jr., Grodent, D. et al. 2002, Nat, 415, 1000
9. Elsner, R., Lugaz, N., Waite, J. et al. 2005, J. Geophys. Res., 110, A01207
10. Bunce, E., Cowley, S., Yeoman, T., 2004, J. Geophys. Res., 109, A09S13
11. Branduardi-Raymont, G., Elsner, R., Gladstone, G. et al. 2004, A&A, 424, 331
12. Branduardi-Raymont, G., Elsner, R., Gladstone, G. et al. 2006, ESA SP-604, 15 (astro-ph/0512249)
13. Branduardi-Raymont, G., Elsner, R., Gladstone, G. et al. 2006b, Planetary and Space Science, submitted
14. Bhardwaj, A., Branduardi-Raymont, G., Elsner, R. et al. 2005, Geophys. Res. Lett., 32, L03S08
15. Strüder, L., Briel, U., Dennerl, K. et al. 2001, A&A, 365, L18
16. Turner, M. J. L., Abbey, A., Arnaud, M. et al. 2001, A&A, 365, L27
17. Singhal, R. P., Chakravarty, S. C., Bhardwaj, A. & Prasad, B. 1992, J. Geophys. Res., 97, 18245

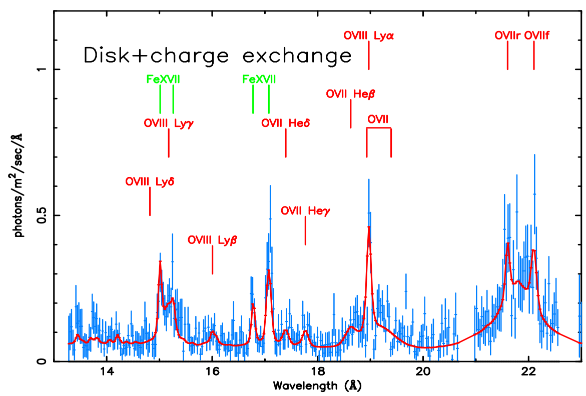

Figure 10. Soft X-ray RGS spectrum of Jupiter fited with a combination of disk and charge exchange line emission components.