RGS SPECTRUM OF KEPLER'S SNR

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We have analysed the *XMM-Newton* RGS data on Kepler's supernova remnant. Even though the source is very extended (200 arcseconds across), we find that we can extract valuable information. The lines are even broader than what the spatial broadening can explain. This is most likely due to the Doppler broadening. The expansion velocity required (representative of the ejecta) is around 3000 km/s.

It is also possible to extract maps in the brightest lines from the RGS data. The maps in the Si K and Fe L lines look like one another (and like the EPIC broad-band map). But the O Lyα map is very different.

1. Source characteristics

Kepler's supernova remnant (SN 1604) is a bright ($F_X \simeq 1.2 \times 10^{-10}$ erg/cm^2/s between 0.15 and 4.5 keV), not too large (100 arcseconds radius) object [1], and as such one of the few Galactic supernova remnants (SNRs) on which the *XMM-Newton* gratings (RGS [2]) may give valuable information. Its distance is estimated at 5 kpc or so, but with a large uncertainty [3]. The interstellar column density is large (3 – 6 $\times 10^{21}$ cm^{-2}) but not enough to absorb the low-energy emission entirely. For more details see [4].

2. Spectral analysis

Kepler was observed by *XMM-Newton* on March 10$^{\mathrm{th}}$, 2001. Kepler fits entirely within the RGS field of view, so our data are representative of the total source spectrum. The exposure time was 32,655 and 31,703 s for RGS1 and RGS2, respectively. Compared with standard RGS data analysis, we have taken several additional steps to account for the source's size:

- We have broadened the source regions, both spatially (most important) and spectrally, to encompass the whole source.
- We have extracted the spectrum without background subtraction (there is no room left for a background region). The spectra contain 103,843 (RGS1, order −1), 46,651 (RGS1, order −2), 150,629 (RGS2, order −1) and 41,782 (RGS2, order −2) counts.
- We have extracted a background spectrum using the same regions on an 'empty' RGS field (provided by T. Tamura). The estimated number of background counts is 2,581 (RGS1, order −1), 988 (RGS1, order −2), 2,553 (RGS2, order −1) and 1,137 (RGS2, order −2).
- We have built the source's profile along the dispersion axis using the EPIC MOS image (projected onto RGS coordinates).
- We have used a development version of rgsrmfgen (1.2) with arguments withmirrorpsf=N withangdistset=Y, replacing the point spread function with Kepler's profile along the dispersion axis. This is similar to what was done in [5]. In that way the response matrix incorporates the spatial broadening.

Fig. 1 shows the RGS spectrum of Kepler, fitted with a Doppler broadened planar shock model within XSPEC. The best fit temperature is 0.54 keV. The interstellar absorption is 4.3 $\times 10^{21}$ cm^{-2}.

The spectrum is dominated by the Lyα lines of Ne (12.135 Å), O (16.005 Å) and N (24.779 Å), the Heα triplets of Si ($\simeq$ 6.7 Å), Mg ($\simeq$ 9.2 Å), Ne ($\simeq$ 13.5 Å) and O ($\simeq$ 21.7 Å), and the Fe XVII line blends ($\simeq$ 15.0 and 17.1 Å).

The abundances of C (no line) and N (bad local fit, see below) were forced to be equal to that of O. The S abundance (no line) was forced to be equal to that of Si. The Ar, Ca and Ni abundances (no strong line) were forced to be equal to that of Fe.

The abundances are all formally very low except Si (1.6): O, Ne, Mg around 0.15 – 0.20; Fe around 0.4, contrary to expectations in a young SNR enriched by the ejecta. This is possibly because the line shapes are not perfectly reproduced

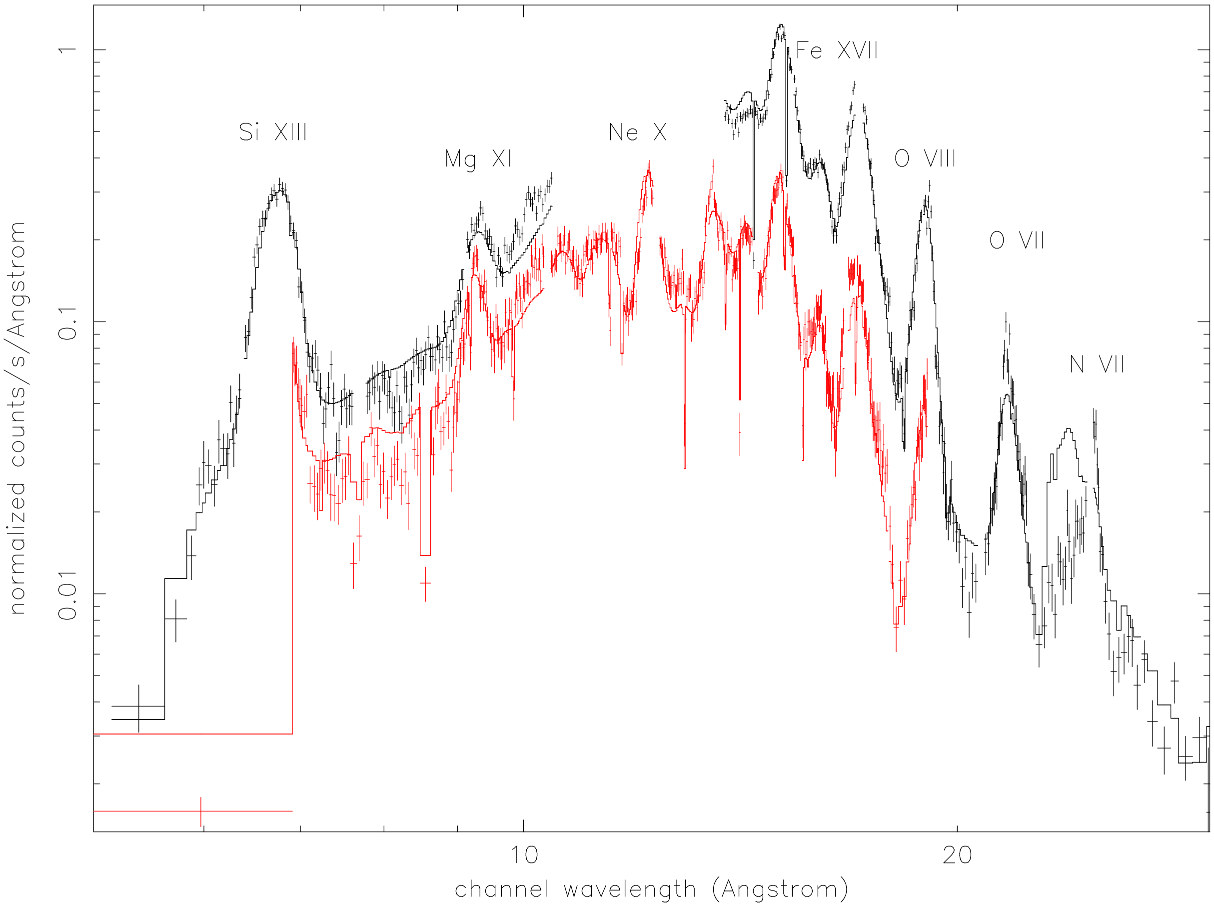

Figure 1. *XMM-Newton* RGS1 spectrum of the entire Kepler SNR. Order −1 is plotted in black (top), order −2 in red (bottom). The XSPEC model is TBabs (gsmooth (vpshock)). This is a planar shock model (with a range of ionisation times) with variable abundances, convolved with a gaussian Doppler broadening and multiplied by interstellar absorption. The best fit velocity width (sigma) is ≃ 3000 km/s. The C statistic improves by about 8000 when the Doppler broadening is entered.

(preventing the lines from rising), or because the single temperature fit does not predict enough lines to fill the holes between the bright lines. The only clear place to see the continuum is around 8 Å (between the Si and Mg Heα lines), where the fit is too high.

The fit is quite bad around 23 Å. This is near the O edge in the interstellar absorption (too strong in the model ?). A bright Ca L line is predicted there next to the N Lyα line but not seen.

The Doppler broadening (in addition to the spatial broadening) is highly significant. It can only be due to the expansion of the SNR. What is measured here is the gas velocity (actually the ejecta velocity, because the ejecta dominate the emission). With a standard compression ratio of 4, the shock velocity $v_{\rm s}$ must be larger than 4/3 the gas velocity, so $v_{\rm s} > 4000$ km/s. This estimate is much larger than that obtained from the width of the Hα line in [6] (more like 2000 km/s). It is more in line with the distance estimate ($D = 4.8 \pm 1.4$ kpc [3]) and the X-ray expansion measurement (0.239 % yr^{-1} [7]), which result in $v_{\rm s} = 5400 \pm 1600$ km/s.

Fig. 2 shows a combined RGS + MOS fit. The EPIC MOS spectrum is very similar to the *ASCA* SIS spectrum [8]. MOS and RGS order −1 have comparable spectral resolution at the Si Heα line for a source that large. The RGS rapidly gets

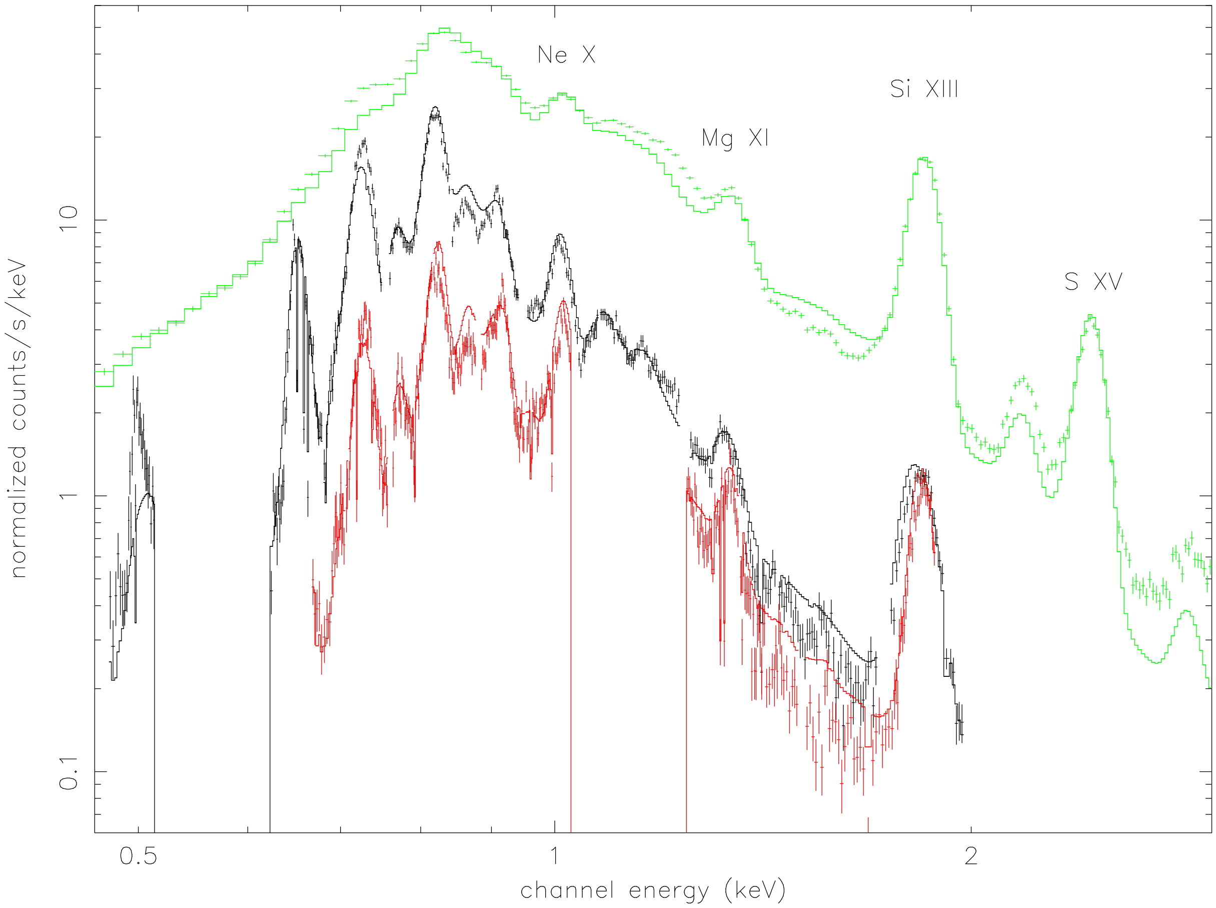

Figure 2. *XMM-Newton* RGS2 (both orders) and EPIC MOS2 (green, top) spectrum of the entire SNR. The model is the same as in Fig. 1 and the parameter values differ only slightly except for the S abundance, here fixed by the S Heα line. Above 3 keV, that single temperature model is way below the MOS data points.

better as energy decreases, and constrains the line emission below 1 keV much better than the MOS does.

The RGS and MOS data agree reasonably well. The model underpredicts the data around the Fe XVII line at 725 eV and around 1.2 keV. It overpredicts the data around 880 eV and in the continuum emission below the Si Heα line. Those deviations are clearly seen in both the MOS and RGS data.

A tentative fit (not shown) of the RGS + MOS global spectrum (up to 10 keV) with a multi-temperature model (c6pvmkl in XSPEC) gives a very bad fit (because it assumes ionisation equilibrium) but favors a double-peaked temperature structure with the first peak around 0.55 keV and the second one above 5 keV.

3. Imaging analysis

It is possible to back-project the photons on the sky around a bright line, assuming all the photons actually have the line's energy (as was done in [9] on Cas A). This results in what we call RGS "images". They are presented in detector coordinates. The conversion from sky coordinates involves a rotation and a flip.

Fig. 3 illustrates how the RGS image looks like next to the brightest line in the spectrum (Fe XVII 15.015 Å). It is difficult to use directly because the line is blended. The cross-dispersion profiles of the RGS and MOS images follow one another perfectly, so the chances are that the

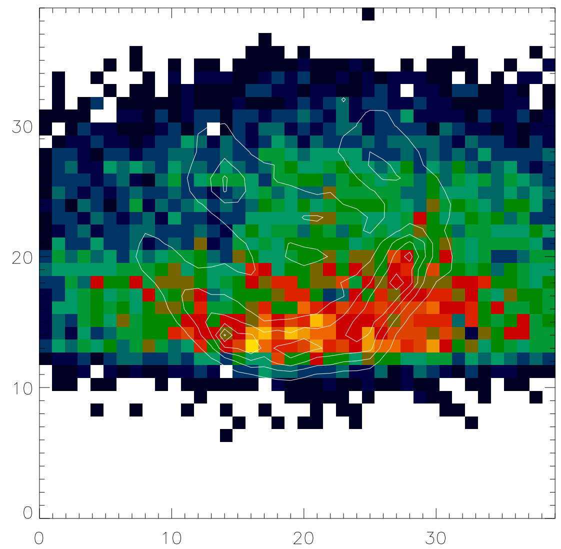

Figure 3. *XMM-Newton* RGS2 image around the Fe XVII line at 15.015 Å. The scale is linear from white to yellow. The EPIC MOS2 image (projected onto ϕ, ψ) in the [0.675,0.885] keV band is overlaid as contours. The image is broadened by the blend with the Fe XVII 15.261 Å line.

MOS image is all right (the Fe XVII lines dominate the spectrum in that band).

Fig. 4 illustrates what can be done on an isolated line (O Lyα). It is clear that the O emission is weak in the bottom ridge (small ψ), compared to Fe (and Si, not shown). The O image actually looks more like the optical image [10] than like the rest of the X-rays. The MOS image (contours) still shows the ridge, probably because it is spectrally contaminated by the Fe XVII lines. In that case the RGS image is clearly better.

Several reasons can explain the difference between the Fe and O images. The absorbing column density could be higher in the ridge, the temperature structure could be such that O is less (or more) ionised there, or it could be a true abundance effect. The image in the O Heα line (not shown) has its peak in the center, and is very weak in the ridge too. This eliminates the possibility that O could be less ionised in the ridge, but it could still be mostly fully ionised. A detailed spectral analysis in several cross-dispersion intervals (beyond the scope of this report) should allow to tell which interpretation is correct.

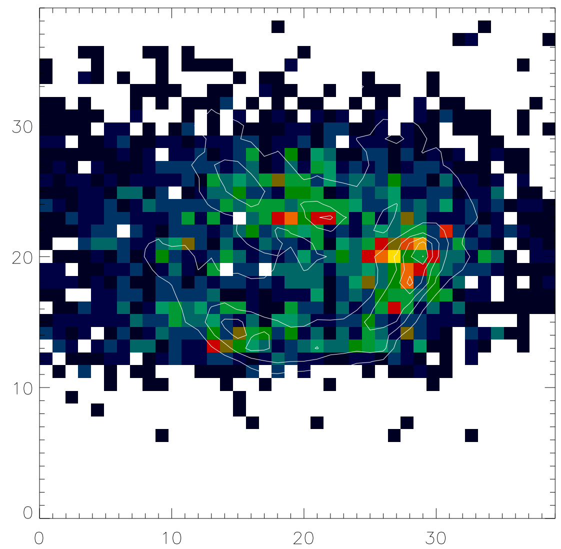

Figure 4. *XMM-Newton* RGS1 image around the O Lyα line at 18.967 Å. The EPIC MOS1 image in the [0.5,0.675] keV band is overlaid as contours. The line is reasonably isolated.

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ACKNOWLEDGEMENTS

This work was carried out as part of a collaborative effort with Gamil Cassam-Chenaï and Anne Decourchelle on *XMM-Newton* Kepler data.