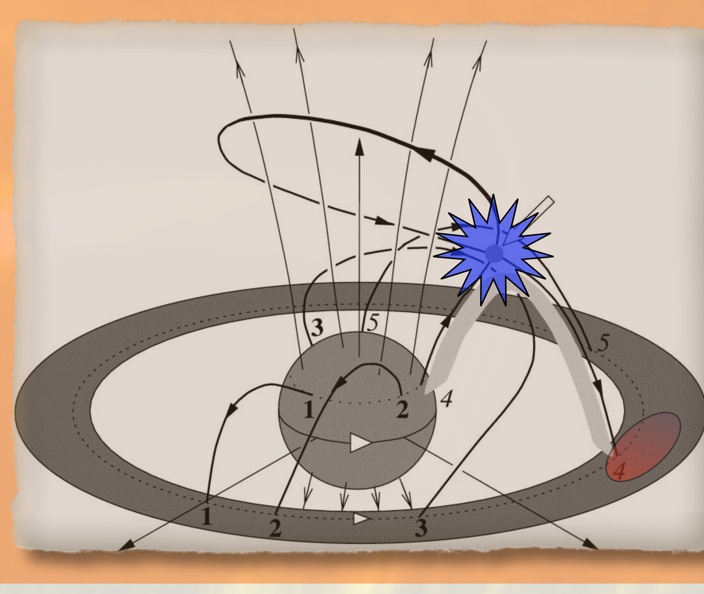
International X-ray Observatory (IXO)

Stellar Flare Dynamics from High-Resolution X-ray Spectroscopy

David P. Huenemoerder (MIT), Rachel A. Osten (STScI), Stephen A. Drake (NASA/GSFC), Ralf K. Heilmann (MIT)
Mark L. Schattenburg (MIT), Marc Audard (ISDC & Observatoire de Geneve)

Why study stellar flares? Here we concentrate on flares from one late-type star to demonstrate the general diagnostic capability of IXO. In addition to specific detail shown here, other areas of significant impact are:

- enough sensitivity and resolution to study *distributions* of flare properties;
- provision of powerful new diagnostics *routinely* (e.g., Fe K fluorescence, line profiles, and line shifts);
- probe *non-equilibrium* plasma states through flare evolution;
- constrain the role of loops and reconnection in the *angular momentum evolution of proto-stellar disks*;
- study the effects of X-ray flare irradiation on circumstellar *disks and planet formation*.



Abstract

Stellar flares on cool stars are a ubiquitous phenomenon in the X-ray spectral region. This most dynamic aspect of coronal activity is possibly a primary source of coronal heating. On the Sun, flares are known to be a manifestation of the reconnection of magnetic loops, accompanied by particle beams, chromospheric evaporation, rapid bulk flows or mass ejection, and heating of plasma confined in loops. Modeling the dynamic behavior allows us to constrain loop properties in ways that cannot be done from analysis of quiescent coronae that necessarily require a spatial and temporal average over some ensemble of structures. Hard X-rays (7-20 keV) cause Fe K fluorescence, whose presence and time profile can also be a powerful diagnostic of flare loop properties.

The recent merger of the US and European/Japanese planned X-ray observatories into the International X-Ray Observatory (IXO) promises unprecedented advances in effective area and resolution for X-ray spectroscopy. While detailed requirements and instrument designs are still being formulated, we believe that it is technically feasible to obtain resolving powers (E/FWHM) of 3000-5000 with effective areas up to 10,000 cm² over the spectral range of 0.3 to 6.0 keV with a grating instrument in conjunction with the imaging detector for zeroth order. A hard X-ray (10-50 keV) camera is also being considered for IXO. We will adopt model instruments, including a grating spectrometer, and perform simulations to explore opportunities IXO might offer for studying high-energy dynamics in the outer atmospheres of stars. In particular, we will explore the ability to obtain time-resolved spectral diagnostics from flares of cool, coronally active stars. We expect IXO to obtain both quantitative improvements (more sources, better sensitivity) and qualitative advances (new constraints on hydrodynamic models).

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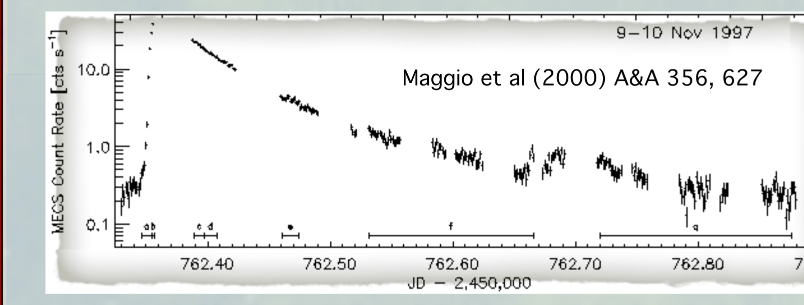
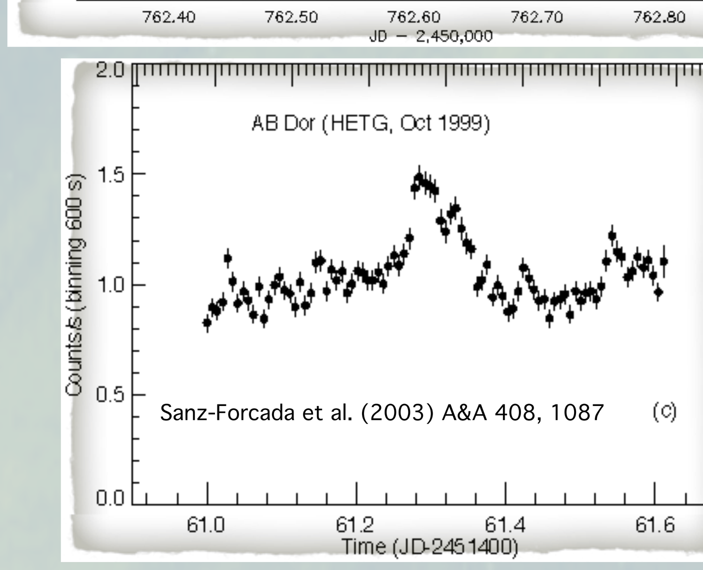
Stellar flares come in many shapes and sizes. Below are two examples for **AB Dor**, a single, rapidly rotating (P=0.5d), very active (f_x~3x10^{-11} ergs/cm²/s) and nearby (14.9 pc) G-star. One flare rose by a factor of 100 in a very short time. The other had only a 1.5 times increase. For our simulations we will adopt an AB Dor-like medium flare with a increase of about 10 times over the base coronal emission.





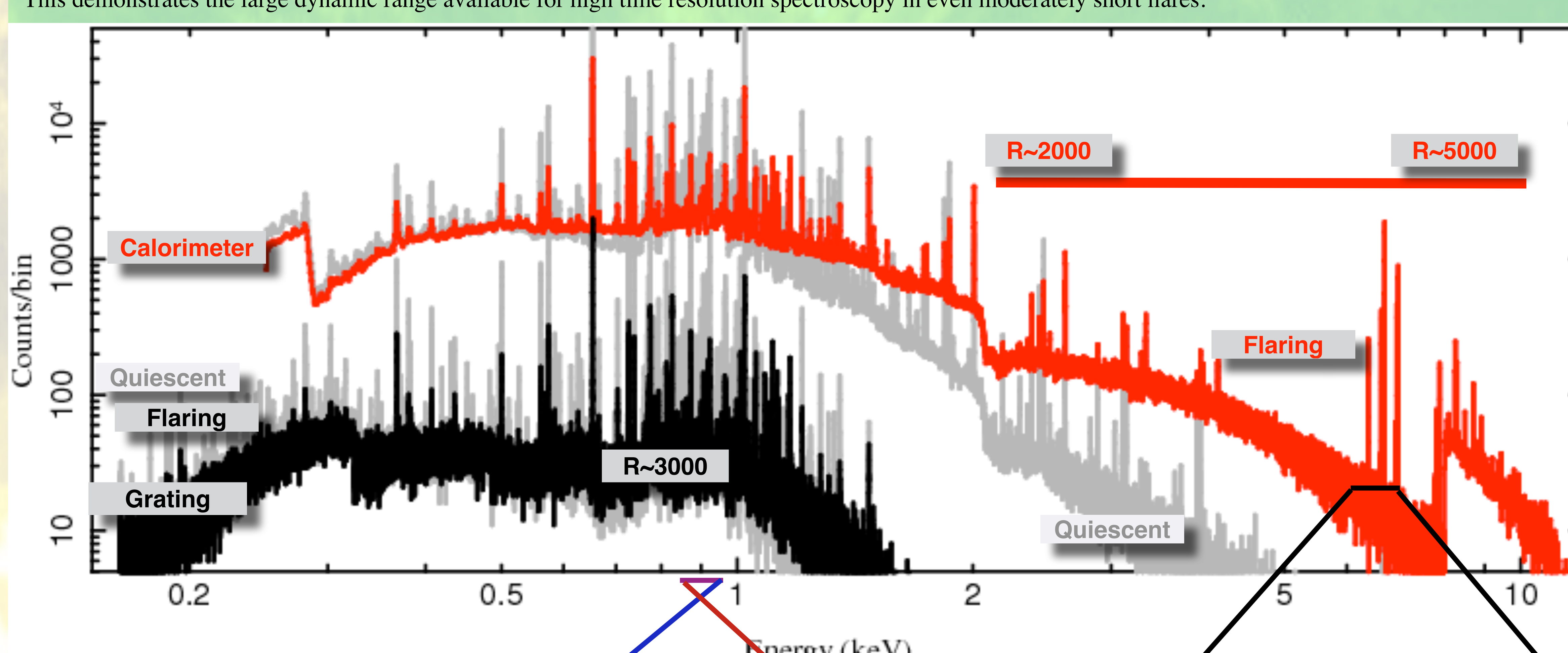
The IXO Instrument Model: To simulate IXO spectra, we have adopted a model instrument which includes a **Critical Angle Transmission (CAT) grating spectrometer** (see **poster 457.10**, Heilmann et al.) which covers about 25% of the mirror aperture and provides about **3000 cm² effective area** from 0.3-1.0 keV at a **resolving power of about 3000**, as read out by a CCD array. The combined transmitted zeroth order and direct beam is simultaneously imaged onto a **calorimeter with a resolution of about 2 eV with an effective area of 1-2 x 10⁴ cm²** from 0.6-6 keV. We used realistic efficiencies for mirrors, detectors, and gratings, and adopted a Lorentzian profile for the CAT grating and Gaussian for the X-ray Microcalorimeter System (XMS).

Simulation and modeling were done in ISIS, the Interactive Spectral Interpretation System (`space.mit.edu/cxc/software/isis`; Houck and DeNicola 2000, ASP Conf., 216, 591) using response matrices to define the instrumental performance. Prototype response matrices are available at `space.mit.edu/home/dph/ixo`.

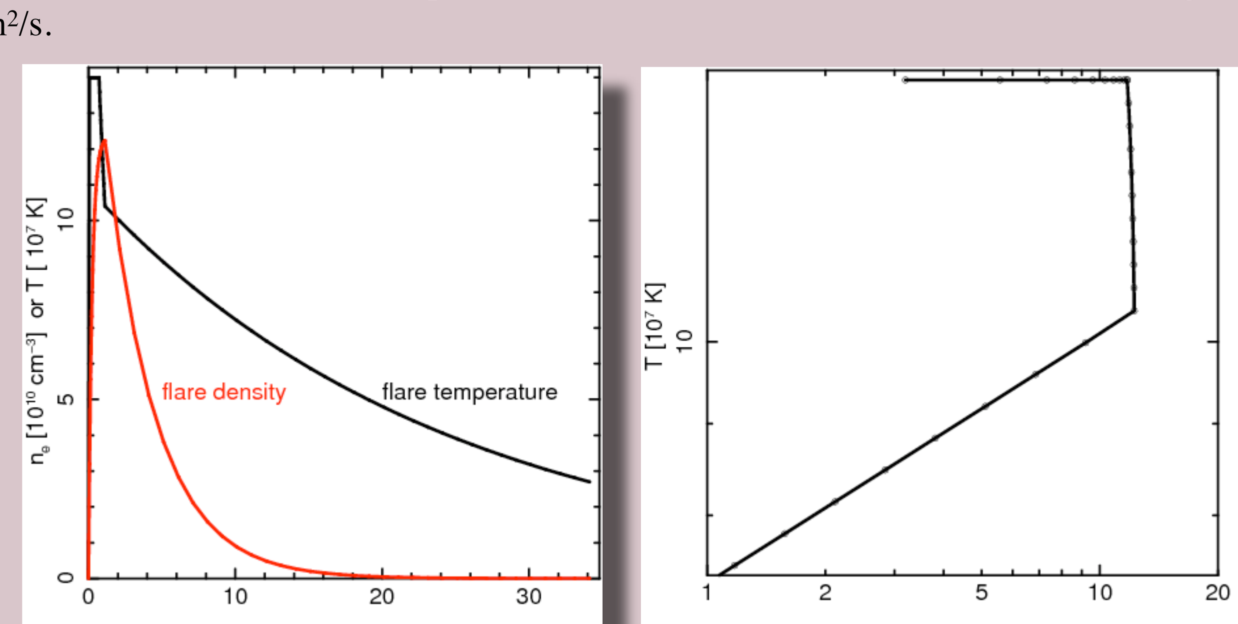
See also:
poster 454.19, H.Marshall et al., "*Science Investigations with a Grating Spectrometer on the International X-ray Observatory*" for an overview IXO/CAT spectroscopic science.
poster 454.15, S.A.Drake et al., "*Stellar Coronae Viewed with High-Resolution X-Rays: The Impact of the International X-Ray Observatory*"

Plasma models: To generate model spectra, we used the Astrophysical Plasma Emission Database (APED/APEC; Smith et al 2001 ApJ 556, L91) with APEC density dependence for the He-like triplets (Smith et al 2002; `cxc.harvard.edu/atomdb/features_density.html`), and integrated the flare model over time intervals. During the initial heat pulse we assumed a bulk velocity of -100 km/s. We assumed a broken powerlaw emission measure distribution (EMD) for the flare plasma, rising to the peak temperature of the model, with a very sharp cutoff, similar in form to flare EMD reconstructions of Reale et al (2004 A&A 416, 733) for Proxima Cen.

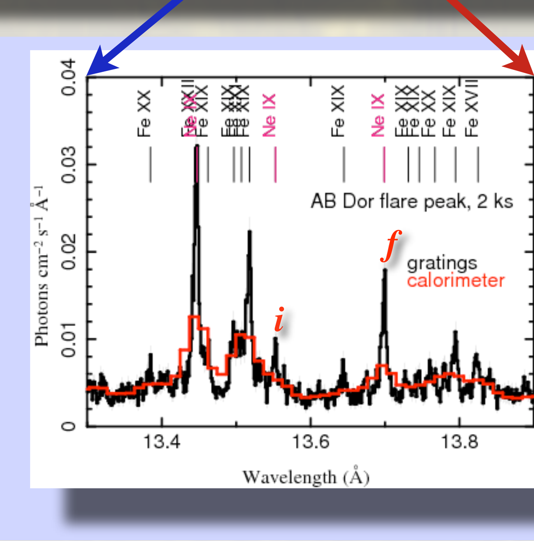
Overview of Simulated Spectra: Here are the counts spectra (in two bins per resolution element) for the first 2 ks (red: calorimeter; black: grating) and for 14 ks of quiescent corona (underlying gray histograms). The calorimeter has higher effective area everywhere, but lower resolving power below about 1.5 keV. This demonstrates the large dynamic range available for high time resolution spectroscopy in even moderately short flares.

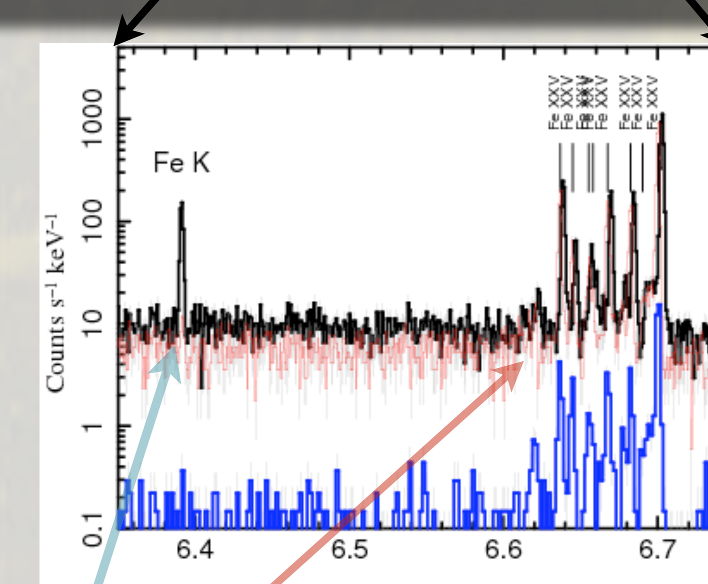


Flare models: We use the theoretical foundation of Reale (2007; A&A 471, 271) which provides diagnostics for the rise as well as decay of a single-loop flare. A flare can be defined by choosing a heating pulse duration, maximum temperature, and loop size. We adopt a corresponding density profile with time which also defines the emission measure evolution (given constant volume). Reale (2007) included parameters for the AB Dor flare observed by Maggio et al (2000): the temperature was quite high, and the density maximum slightly lags the temperature peak. The figures below show our adopted temperature and density evolution. Our peak emission measure was 5x10^{53} cm^{-3} over a constant base coronal emission measure a factor of ten lower, such as observed with Chandra by Sanz-Forcada et al (2003). Peak and quiescent fluxes were about 40 x 10^{-11} and 3 x10^{-11} ergs/cm²/s.

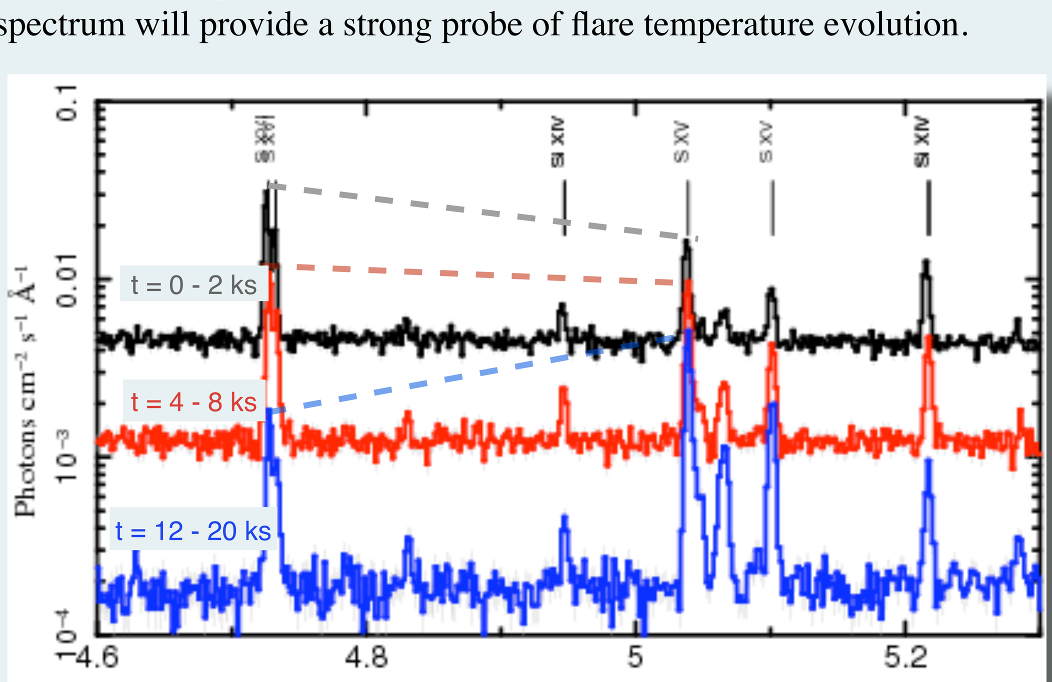


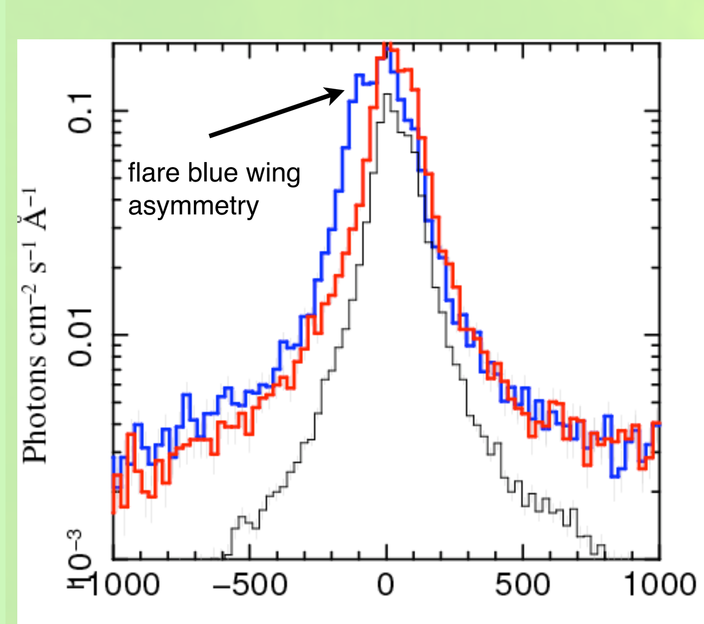
Flux density in the **Ne IX He-like triplet** region. At these wavelengths, the grating (black) has significantly higher resolving power than the calorimeter (red). The Ne IX forbidden (*f*; 13.7A) to intercombination (*i*; 13.55 A) line ratio is an important density diagnostic. Also available in the spectra for coronal density diagnoses are Mg XI (9.2A, 1.35 keV), O VII (22A, 0.56 keV), N VI (29A, 0.43 keV), and C V (41A, 0.30 keV).

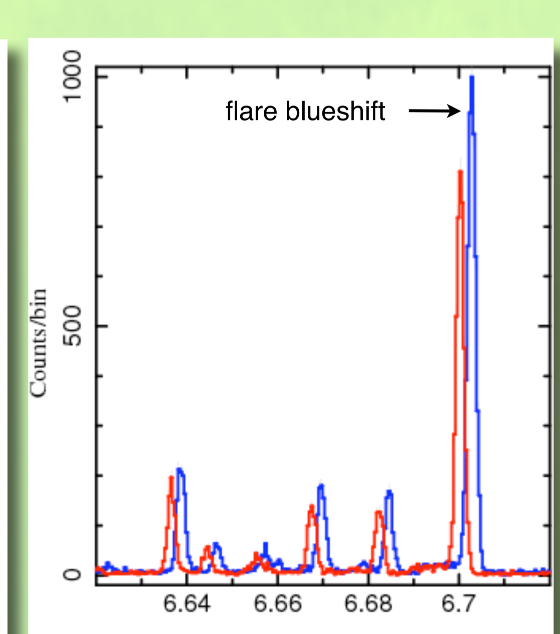




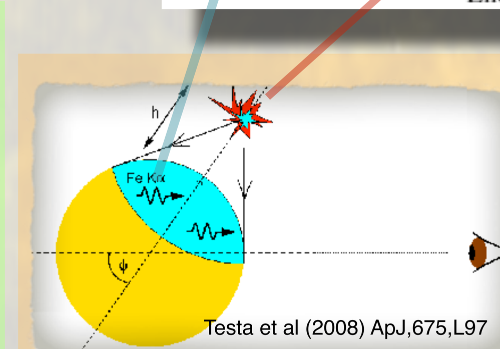
Temperature diagnostics: The He-like to H-like line ratios are temperature sensitive. Below are the S XVI and S XV resonance lines for three intervals during the flare: 0-2 ks (black), 4-8 ks (red) and 12-20 ks (blue). Other ratios are sensitive to higher temperatures (Ar, Ca) and some to lower (Si, Mg, Ne, O). The high energy continuum is also a very good diagnostic of the highest temperatures. The high sensitivity and high resolution across the spectrum will provide a strong probe of flare temperature evolution.





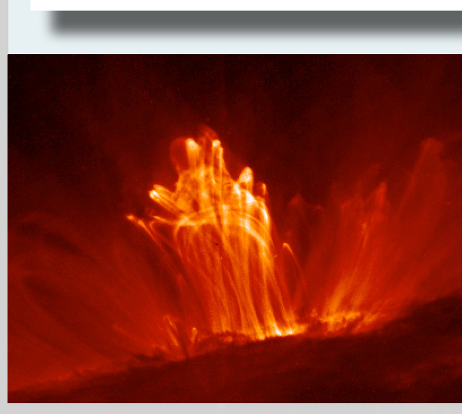
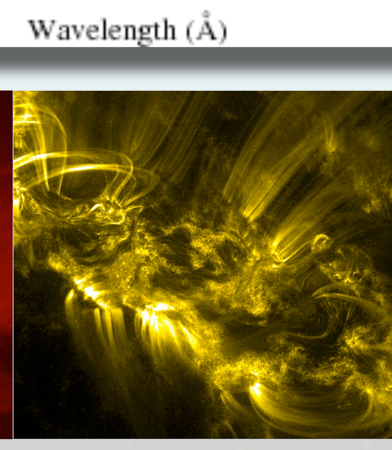


Dynamics: High spectral resolution allows us to probe bulk and turbulent flows in the hot flare plasma as well as in the cooler corona. Our flare model imposed a 100 km/s flow during the initial thermal pulse (t<2ks), and this is easily seen in the Fe XXV lines (near left): blue is for t = 0-2ks, and red is 2-4 ks. At the far left is O VIII for the same times as well as later times (gray). The oxygen lines show asymmetries since the model had a small amount of cooler plasma in the flare.



Line detail in the **Fe K, Fe XXV region**. The flare peak, 0-2ks, is in black. Red is 2-4 ks, and blue is from 12-20 ks. Flare illumination of the photosphere with photons of E > 7 keV can cause Fe K fluorescence. The yield depends upon the flare height and photospheric Fe abundance. We assumed a yield of 2% to model Fe K, which fades extremely rapidly vanishing by 3ks in this model. IXO can provide detailed tests of flare geometry.

Solar flare loop images are from the Transition Region and Coronal Explorer, TRACE, which is a mission of the Stanford-Lockheed Institute for Space Research, and part of the NASA Small Explorer program.

Conclusions: The IXO large throughput combined with high resolving power grating and imaging spectrometers together will make a powerful instrument for time-resolved studies of flares in cool stars. Measurements of density, temperature, velocity throughout a flare *rise and decay* will provide critical tests of flare loop hydrodynamic models.