Nonparametric Estimation of Intrinsic Properties of Faint X-ray Sources

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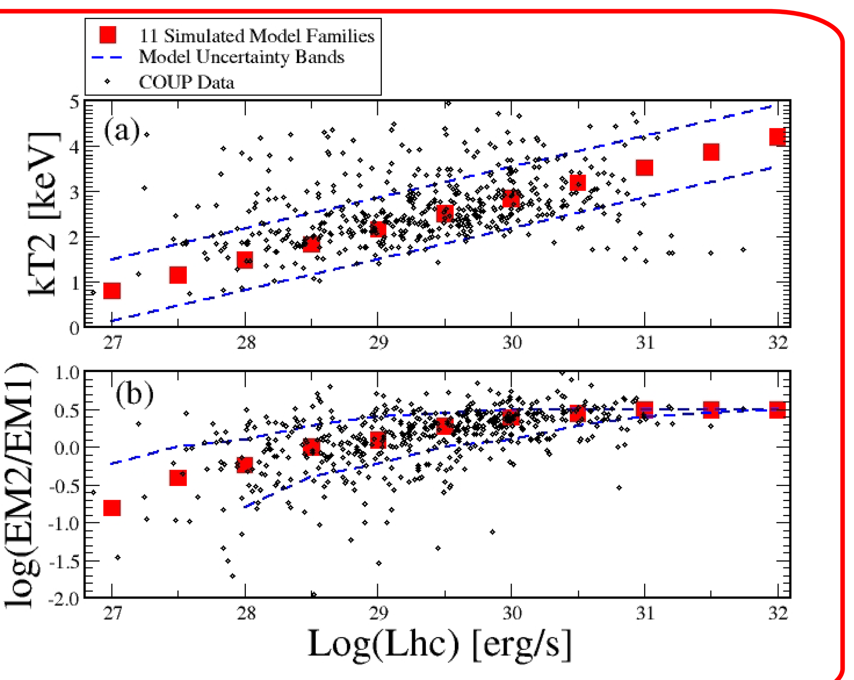
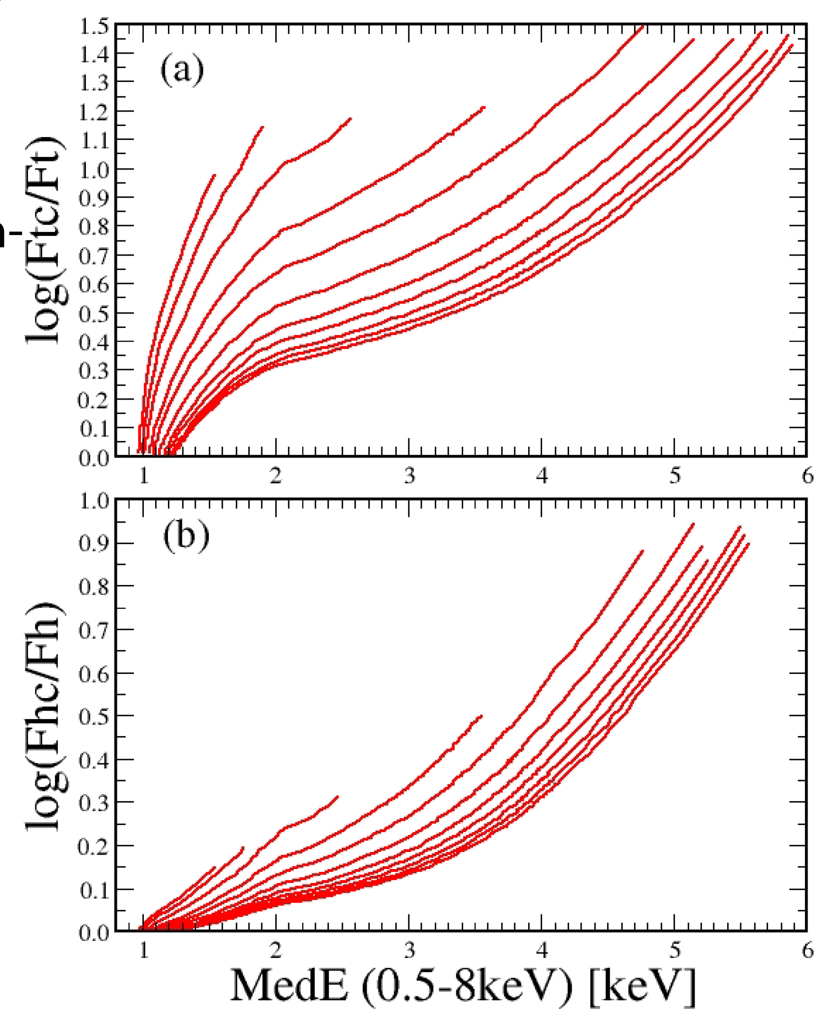
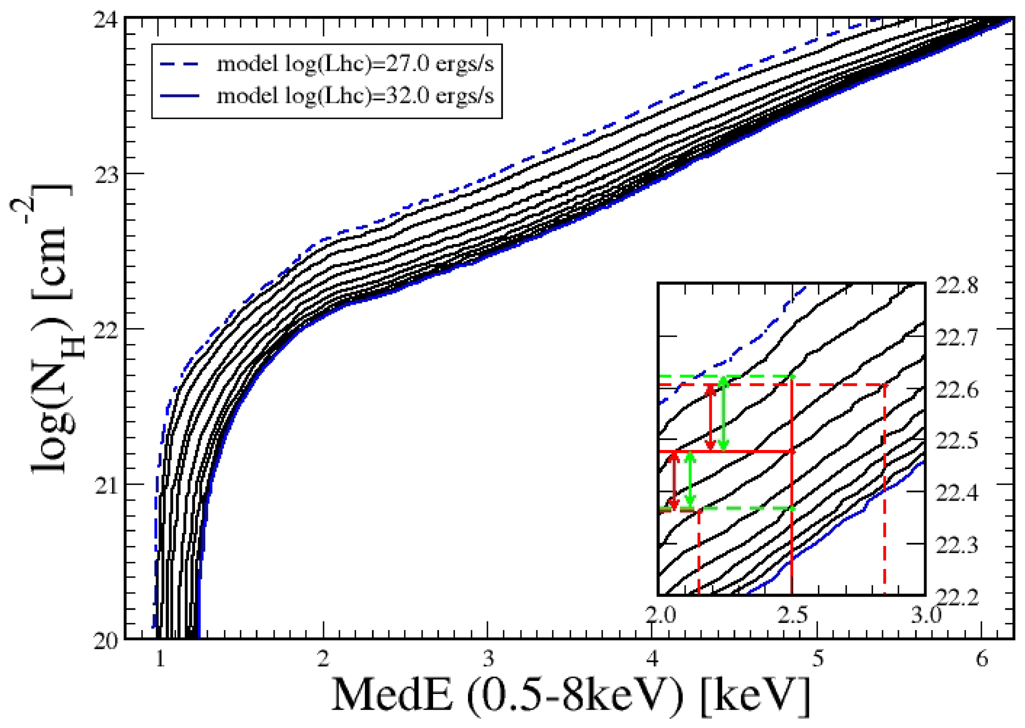
1. INTRODUCTION X-ray sources with very few counts can be identified with low-noise X-ray detectors such as the Advanced CCD Imaging Spectrometer onboard the Chandra X-ray Observatory. These sources are often too faint for parametric spectral modeling using well-established methods such as spectral fitting with XSPEC. We discuss the estimation of apparent and intrinsic broad-band X-ray fluxes and soft X-ray absorption from gas along the line-of-sight to these sources, using nonparametric methods. Apparent flux is estimated from the ratio of the number of source counts to the instrumental effective area averaged over the chosen band. Absorption and intrinsic flux are estimated by comparing the apparent median energy of the source photons and apparent source flux with those of high signal-to-noise spectra that were simulated using spectral models characteristic of much brighter sources of similar class previously studied in detail. This method is conceptually similar to the long-standing use of color-magnitude diagrams in optical and infrared astronomy. Our nonparametric method is tested using the spectra of ~2000 pre-main sequence (PMS) stars in the M 17 rich stellar cluster. We show that the line-of-sight absorption and broad-band fluxes can be determined with little bias and reasonable accuracy using these observable photometric quantities without employing the often uncertain methods of non-linear parametric spectral modeling. Our results are obtained for thermal spectra characteristic of stars in young stellar clusters, but similar results should hold for other classes of faint X-ray sources.

2. SPECTRAL MODELS for PMS STARS Prior study of a bright calibration sample of young stars in the Orion Nebula indicated a generic spectral model for this class of X-ray sources: a two-temperature thermal plasma with the cooler temperature fixed, and the hotter temperature and ratio of emission measures between hot & cool components scaled to X-ray luminosity. This allows us to explicitly set and simulate X-ray models of PMS stars (11 model families over a grid of absorption column densities --- to get a large number of high signal-to-noise simulated spectra).



3. MAPPING APPARENT to INTRINSIC PROPERTIES
Analysis of the simulated data calibrates the dependencies of spectral models on observable quantities (=calibration data): absorbing X-ray column density on apparent median energy (figure below), and intrinsic to apparent flux ratio on median energy (figure to the right).

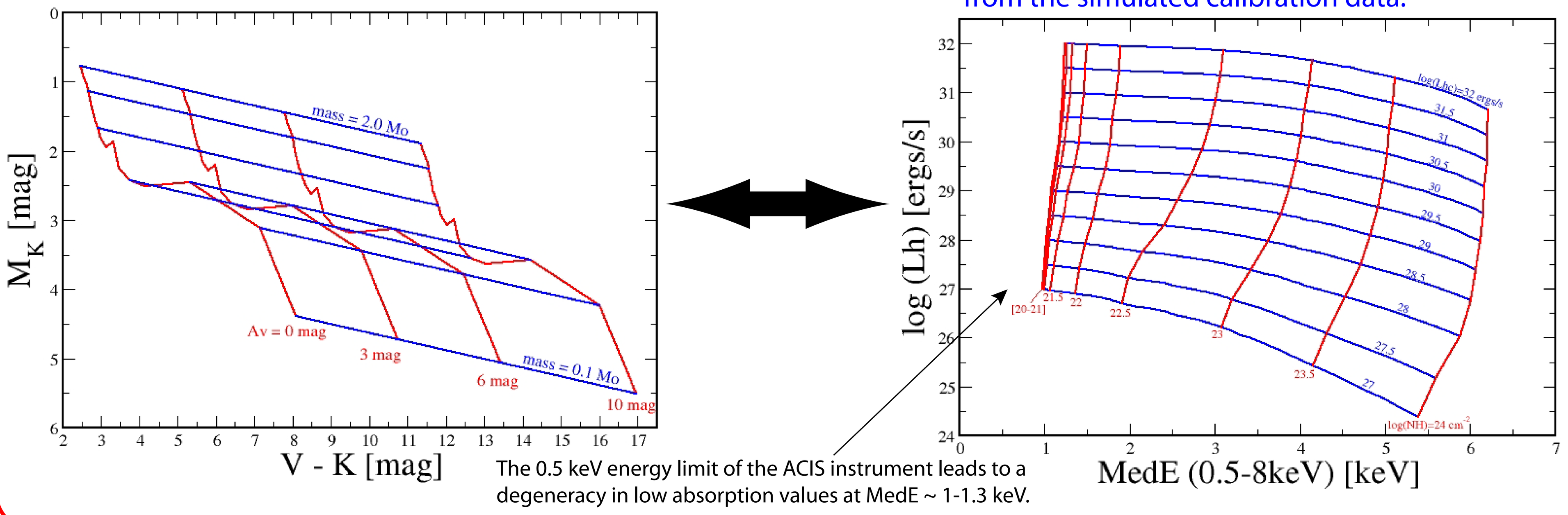




The insert diagram (figure above) illustrates how the median energy errors are propagated to estimate both statistical (red arrows) and systematic (uncertainties in our knowledge of the X-ray spectral model; green arrows) errors on $\log(N_H)$. Using calibration curves from the right-hand panels above, errors on median energy and apparent flux are propagated to estimate errors on intrinsic hard-band (Fhc) and full-band (Ftc) fluxes (in units of ergs/cm^{-2}/s).

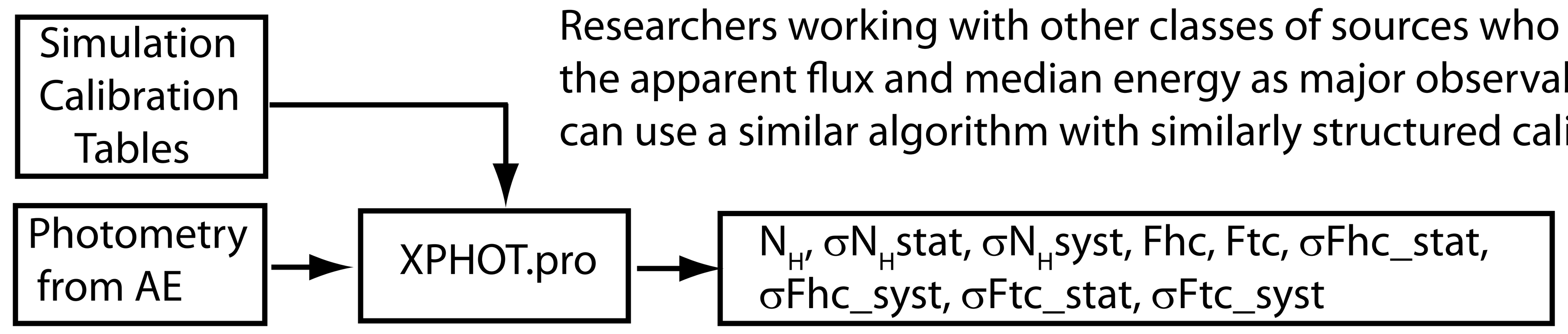
4. ANALOGY to OPTICAL-INFRARED ASTRONOMY Conceptually our method is similar to the long-standing use of color-magnitude diagrams in optical and infrared astronomy. The apparent hard-band luminosity (Lh) is analogous to OIR (e.g. K-band) magnitude; the apparent full-band median energy (MedEt) is analogous to OIR color (e.g. V-K); the derived absorbing column density (NH) -- to visual absorption (Av); the derived intrinsic hard-band luminosity (Lhc) -- to stellar mass:

The X-ray color-magnitude diagram derived from the simulated calibration data.

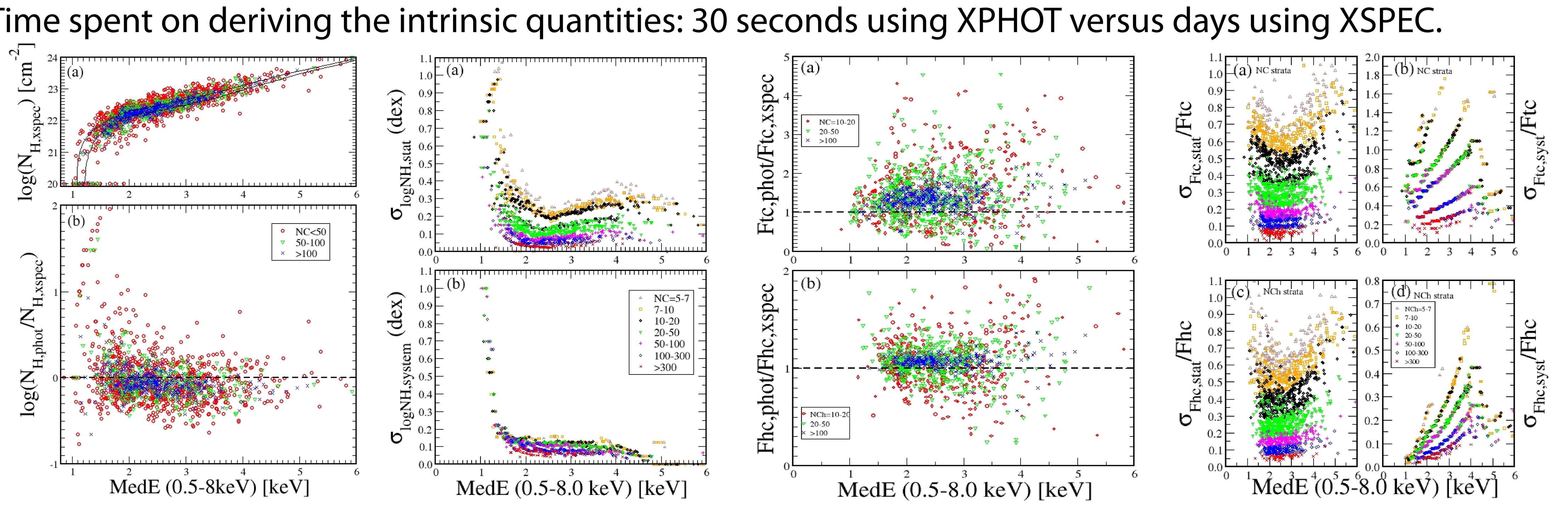


5. IMPLEMENTATION Photometric properties of weak X-ray sources can be derived using the ACIS Extract package (http://www.astro.psu.edu/xray/docs/TARA/ae_users_guide/). The algorithm for obtaining intrinsic quantities (by passing source photometry information through simulated calibration data), as well as PMS calibration tables, and the IDL implementation of the algorithm can be found at http://www.astro.psu.edu/users/gkosta/XPHOT/ .

Researchers working with other classes of sources who choose to use the apparent flux and median energy as major observable quantities can use a similar algorithm with similarly structured calibration tables.



6. APPLICATION to M17 X-RAY SOURCES We illustrate our method using the large dataset of ~2000 PMS candidate stars in the M17 region. The derived absorption and intrinsic flux estimates are compared between our nonparametric (XPHOT) and parametric (XSPEC fitting followed by visual inspection) methods. Time spent on deriving the intrinsic quantities: 30 seconds using XPHOT versus days using XSPEC.



Results: 1) When MedEt < 1.7 keV, only an upper limit on $\log(N_H)$ (<22cm^{-2}) can be inferred; 2) $\log(N_H)$ can be estimated to better than 0.33/0.25/0.18dex for 7-2 /20-50 / >50 count sources; 3) Errors on Fhc are better than 60% (equivalent to 0.2dex in logF) for sources with 7 hard-band counts; 4) Similar accuracy on Ftc is archived only for sources with >100 full-band counts; 5) There is a hint that the parametric (XSPEC) method with 1-T fits does not recover some fraction of the soft intrinsic PMS X-ray emission. This is further supported by a comparison of the spectral fit results between the deep 840~ks COUP and earlier shallower 80~ks Chandra exposures.

7. APPLICATION to OTHER CLASSES of FAINT X-RAY SOURCES Other classes of X-ray sources will exhibit different intrinsic spectral shapes with different dependencies on observable quantities. Researchers working with other classes of X-ray sources should generate their own Calibration Tables to use with XPHOT.pro. However, to explicitly define and simulate X-ray models for any class of X-ray sources, relationships between intrinsic and/or observable quantities that relate power (flux, luminosity, count rate) to a spectral shape (plasma temperature, powerlaw index, hardness ratio) are required. For example, 1) A statistical relationship is seen between the powerlaw index and luminosity in high redshift AGNs (Shemmer et al. 2006; Saez et al. 2008, Figure 17 in the latter). 2) Close binary star systems with accreting black holes typically show two spectral components, a thermal disk and a nonthermal powerlaw. The relative strength of the components scales with the source luminosity and hardness ratio (Figures 4-8 in Remillard & McClintock 2006).

8. CONCLUSIONS We show that: 1) Absorption $\log(N_H)$ and intrinsic hard-band flux Fhc can be measured with reasonable accuracy using apparent flux and median energy; Ftc estimates are less reliable; 2) The IDL implementation of our method (XPHOT.pro) is provided; time needed to derive intrinsic properties for ~2000 X-ray sources is < 1 minute; 3) The method is especially useful for statistical studies of rich stellar clusters --- for constructing column density map and performing X-ray luminosity function analysis; 4) Nonparametric results also can be used as initial and/or frozen parameters to use with the parametric XSPEC method for fine-tuning of spectral properties; 5) Researchers working with other classes of X-ray sources should explicitly define and simulate their own models to construct calibration tables to use with XPHOT.pro .