

**X-RAY GRATING
SPECTROSCOPY WITH
CHANDRA AND XMM-NEWTON**

*Collisional Plasma, Photoionized
Plasma, and What's in Between*

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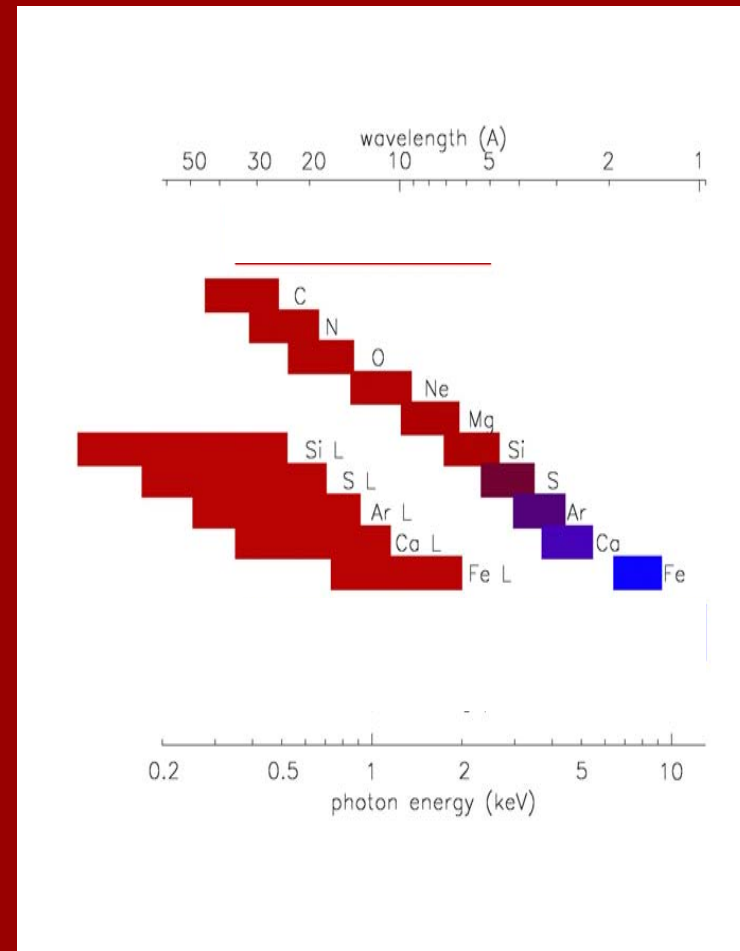
Kurt van der Heyden, Jelle Kaastra,
Bert Brinkman

Outline

- ❖ **Introduction**
 - **The Soft X-Ray Band, *Chandra* and *XMM-Newton*, Collisional and Photoionized Plasma**
- ❖ **Collisional Plasma: X-Ray Spectra of Supernova Remnants**
 - **Transmission vs. Reflection Gratings, Magellanic Clouds Sample, Search for Non-Equilibrium Ionization**
- ❖ **Photoionized Plasma: X-Ray Spectra of Seyfert 2 Galaxies**
 - **Low Temperatures, Measuring Column Densities in Emission, Searching For Hot Gas (Starburst)**
- ❖ **In Between: Warm Hot Intergalactic Medium**
 - **First Steps in Plasma Modeling**

The X-Ray Band: Highly Ionized Atoms

- ❖ The soft x-ray band (0.2 – 12 keV \sim 1 to 60 Å) comprises spectral lines from many K-shell and L-shell ions pertaining to all of the cosmically abundant elements from C to Ni.
- ❖ The x-ray band is uniquely compact. It includes several ions from each element and many lines from each ion.
- ❖ This wealth of lines and ions allows for elaborate and robust diagnostics over a wide range of temperatures, densities, column densities, ionization states, and elemental abundances.



X-Ray Astronomy: Brief History

- ❖ The discipline of X-Ray Astronomy was born in 1962 with the discovery of Scorpius X-1.
- ❖ Over the years x-ray observatories have revealed a diverse collection of x-ray sources ranging from nearby stars to distant galaxies.
- ❖ However, due to instrumental limitations, spectroscopy has been largely unavailable. Spectroscopy is crucial for constraining physical conditions at the source.
- ❖ It wasn't until the launches in 1999 of *Chandra* and *XMM-Newton* that x-ray line-resolved spectra have become available regularly.
- ❖ With this recent achievement, the x-ray branch of astronomy has caught up with other wavebands in using spectroscopy to perform quantitative investigations of cosmic objects.

A New Era in X-Ray Astrophysics: *Chandra and XMM-Newton*

❖ *The Chandra Observatory*

Launched by NASA July 23, 1999

Payload:

1 telescope, 2 CCD cameras,
2 transmission grating
spectrometers (HETGS & LETGS)

❖ *XMM-Newton*

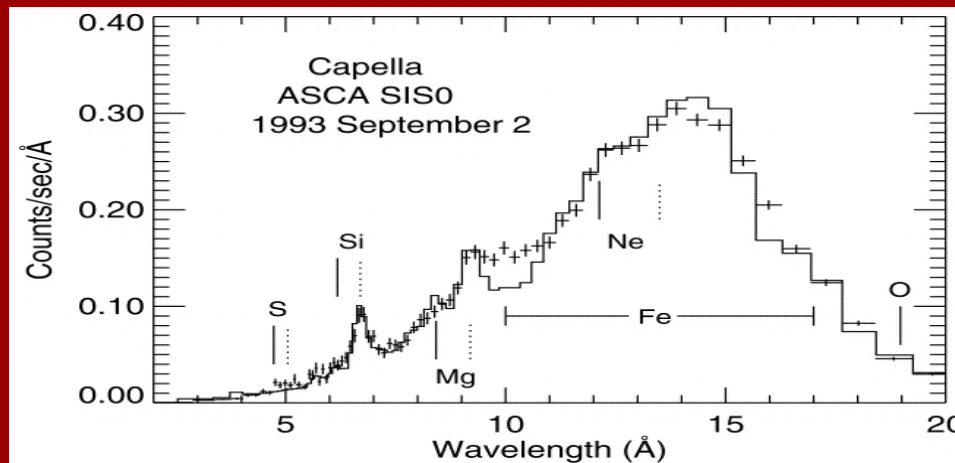
Launched by ESA on
December 10, 1999

Payload:

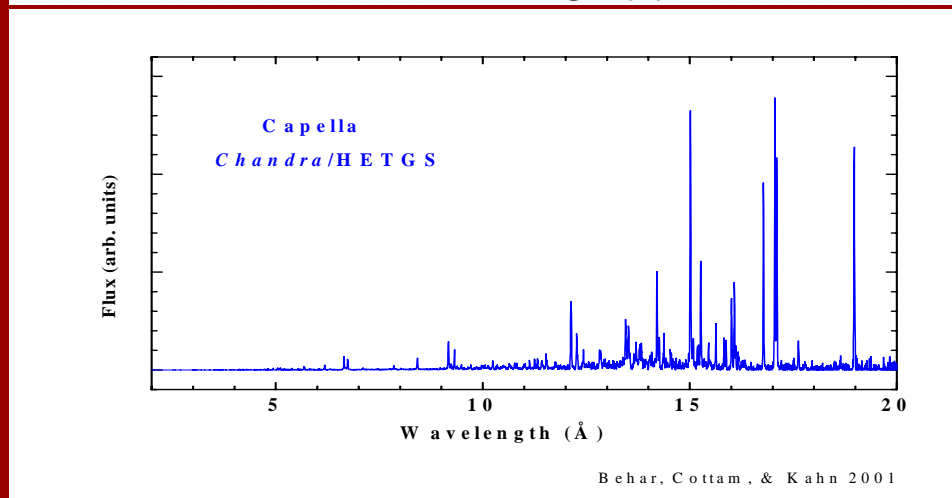
3 telescopes, 3 CCD cameras,
2 reflection grating spectrometers
(RGS), 1 Optical/UV monitor



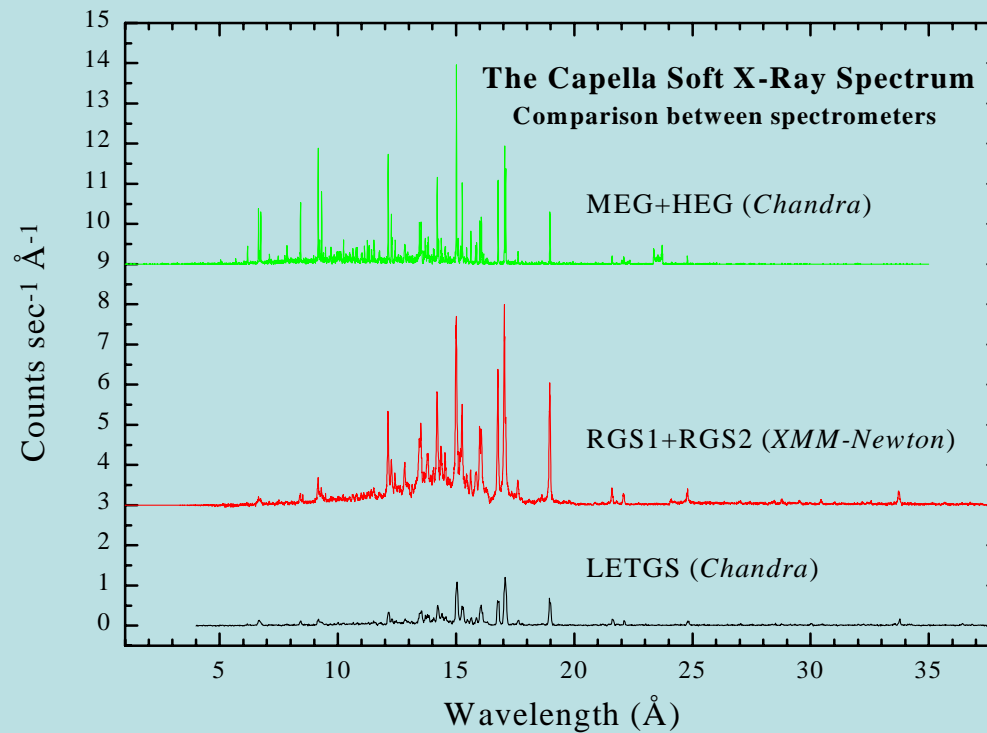
The Difference That High Spectral Resolution Makes



ASCA spectrum
from Brickhouse,
Dupree, Edgar et al.
2000



Capella with the Various Gratings



Ehud Behar, Oct. 2000

Collisional and Photoionized (X-Ray) Plasmas

Collisional Plasma

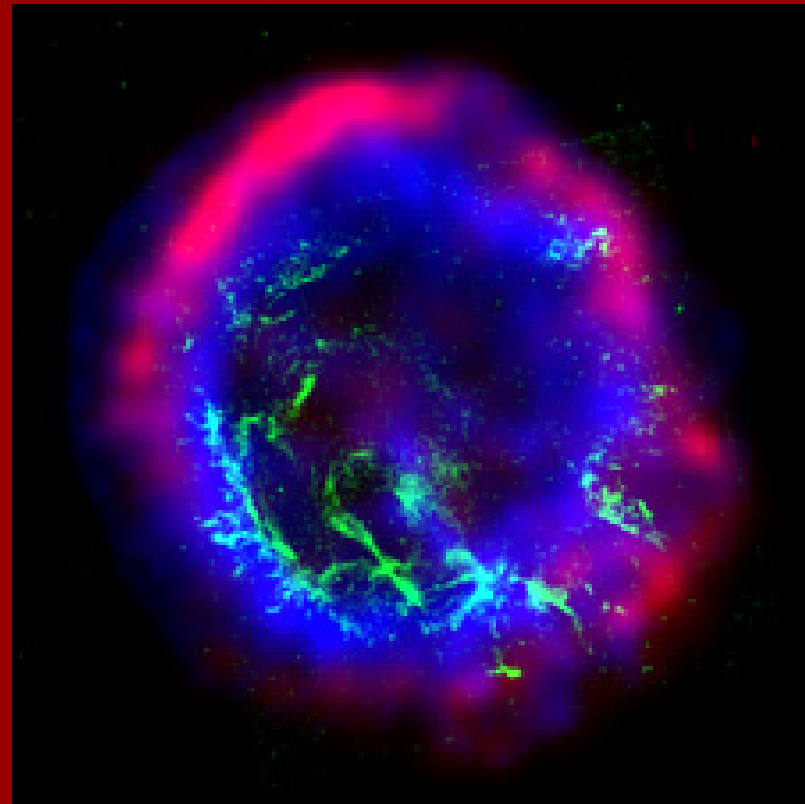
- ❖ External energy source (high temp. \sim keV)
- ❖ Electron impact ionization (T_e)
- ❖ Recombination: DR ($\Delta n > 0$) and RR
- ❖ X-ray line production: collisional excitation and ensuing cascades
- ❖ Stellar coronae, SNRs, galaxies, clusters, laboratory (generally)

Photoionized Plasma

- ❖ Only radiation field (low temp. \sim eV)
- ❖ Photoionization ($\xi = L / nr^2$)
- ❖ Recombination: RR and DR ($\Delta n = 0$)
- ❖ X-ray line production: recombination, cascades, and photoexcitation
- ❖ X-ray binaries, AGN, Z-pinch experiments

Collisional Plasma: Supernova Remnants

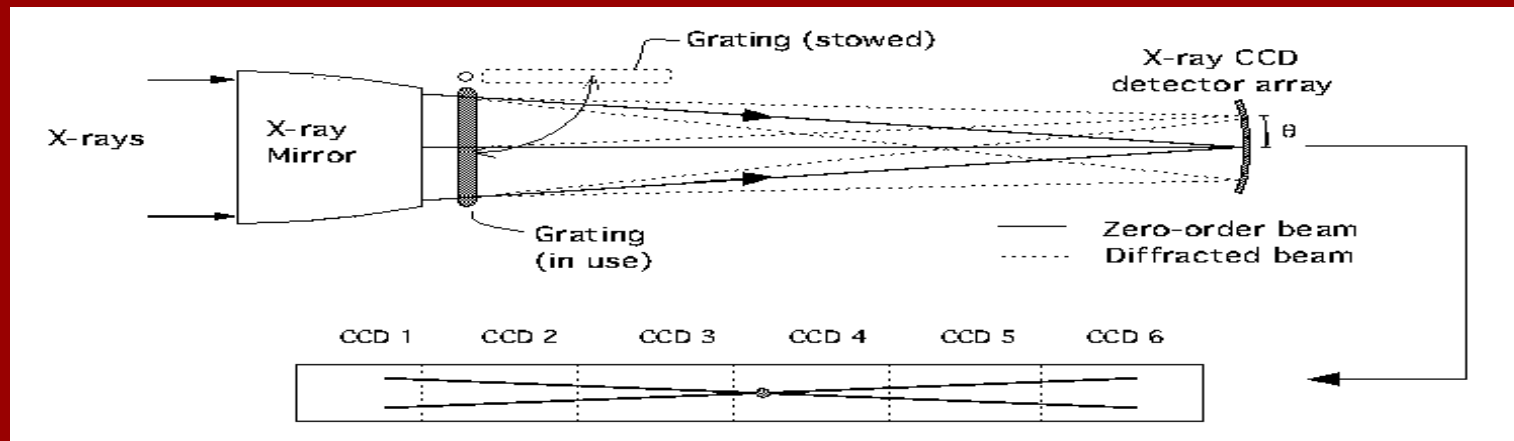
- ❖ A supernova explosion throws out matter ($v \sim 10,000$ km/s) that plows through the ambient gas ($n \sim 1$ cm⁻³) producing shock waves in the ISM as well as in the SN ejecta. The shocks heat the gas ($kT \sim 0.1 - 2$ keV) and create a shell-like remnant.
- ❖ The low-density hot gas shines in x-rays (and radio) for many thousands of years.



E0102 from the *Chandra* website

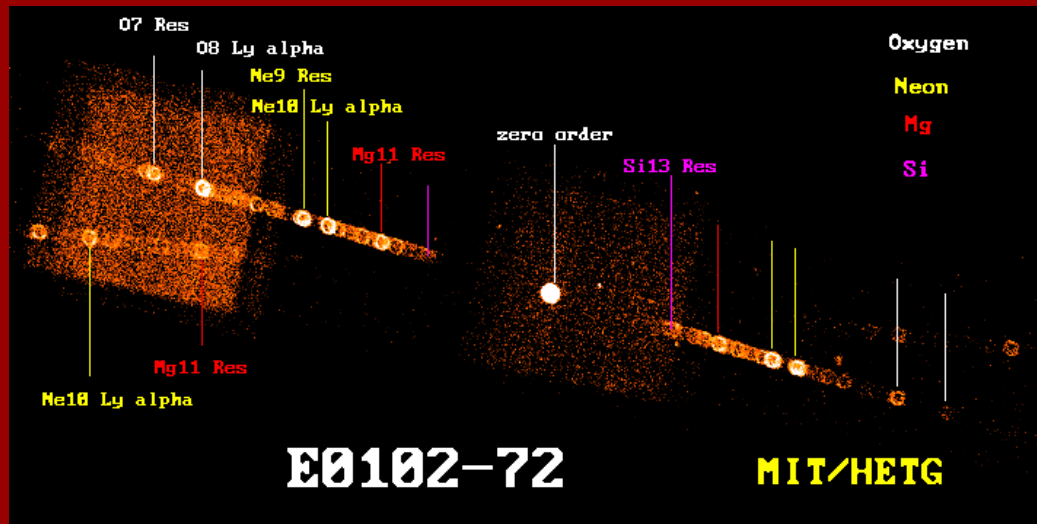
Slitless Spectroscopy of Extended Sources: The Challenge

The Chandra Design: Transmission Gratings

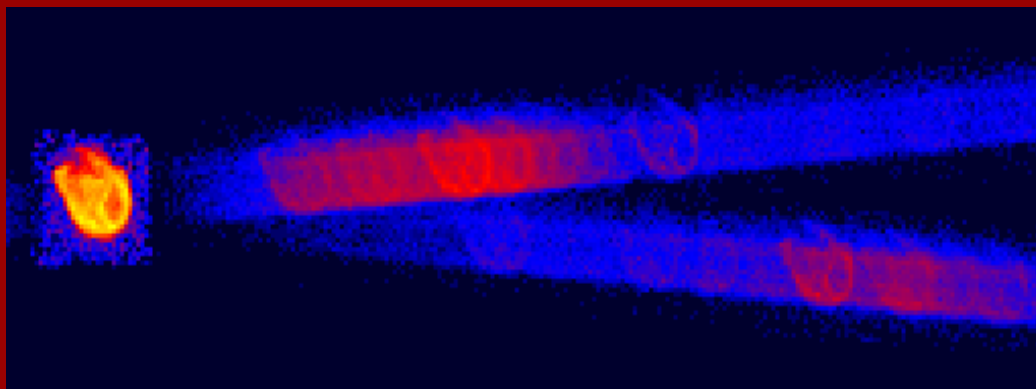


- ❖ **Dispersion:** $d (\sin \theta + \sin \alpha) = m \lambda$ ($\Delta \theta = \Delta \alpha$)
- ❖ **Extension in wavelength space** (MEG: $d = 0.4 \mu\text{m}$) =>
 $\Delta \lambda = d / m \cos \alpha \Delta \alpha \cong 4 \times 10^{-4} \text{ mm} (10^6 \text{ \AA/mm}) \Delta \alpha = 400 \text{ \AA} \Delta \alpha$
- ❖ **1 arcmin $\sim 0.1 \text{ \AA}$**

Extended SNR's with *Chandra/HETG*



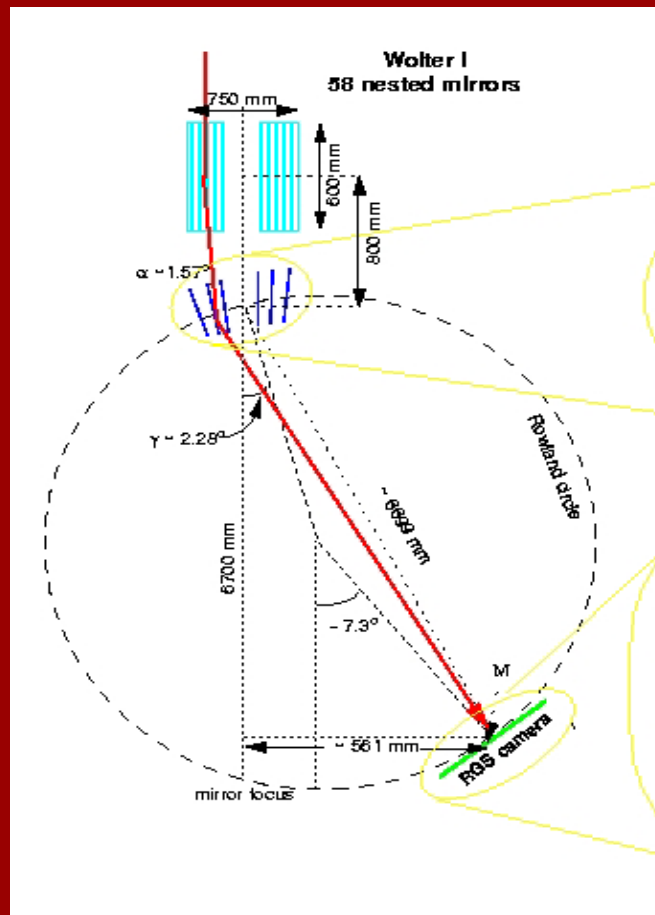
SNR E0102 (SMC),
real data



SNR N132D (LMC),
Simulation by
J. Houck
(*Chandra* web site)

Slitless Spectroscopy of Extended Sources (cont.)

The XMM-Newton Design: Reflection Gratings

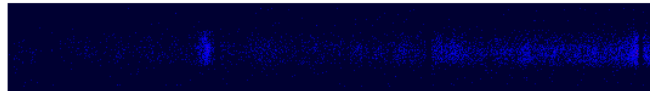


- ❖ **Dispersion:**
 $d (\cos \beta - \cos \alpha) = m \lambda$
- ❖ **In wavelength space**
 RGS: $d = 1.5 \mu\text{m}$, $\alpha \cong 1.5^\circ \Rightarrow$
 $\Delta \lambda = d / m \sin \alpha \Delta \alpha \cong$
 $1.5 \times 10^{-3} \text{ mm } 0.03 \Delta \alpha \cong$
 $50 \text{ \AA } \Delta \alpha$
- ❖ **1 arcmin $\sim 15 \text{ m\AA}$**

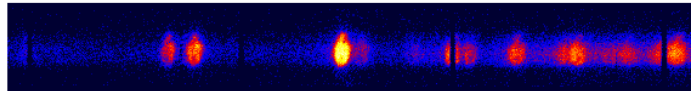
Extended SNR's with *XMM-Newton/RGS*

LMC SNR N132D

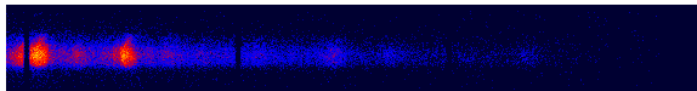
*XMM/Newton RGS Team
m=-1 spectroheliograms*



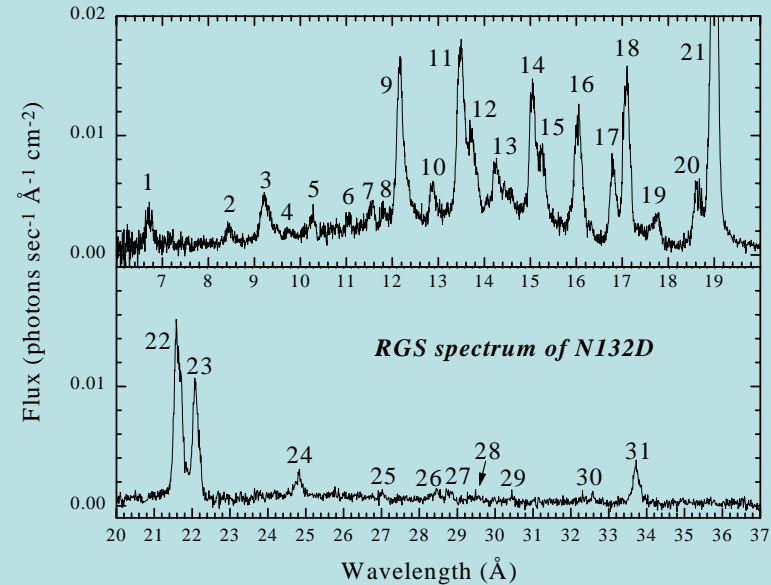
long (38-25) wavelength



medium (25-12) wavelength

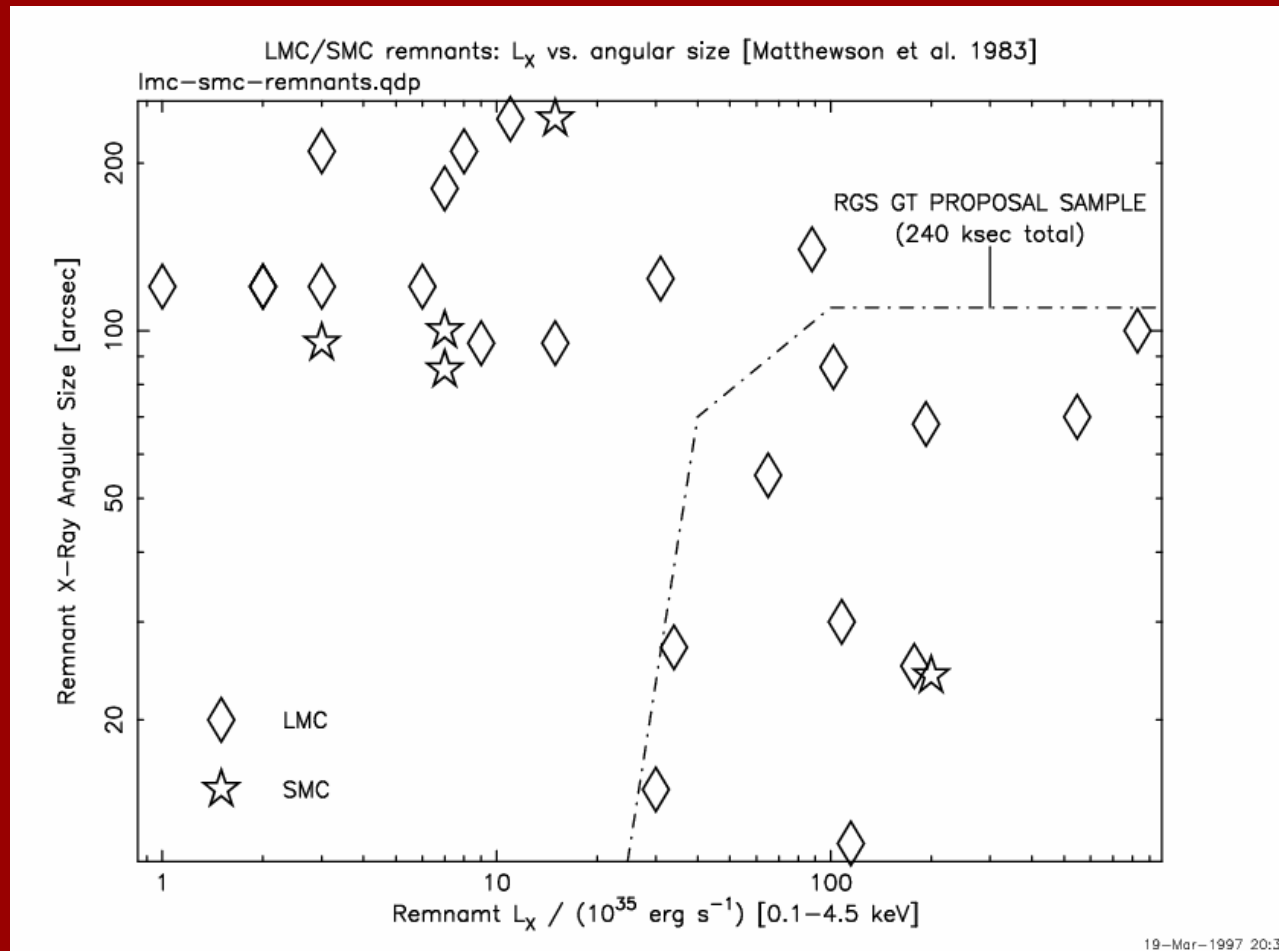


short (12-5) wavelength

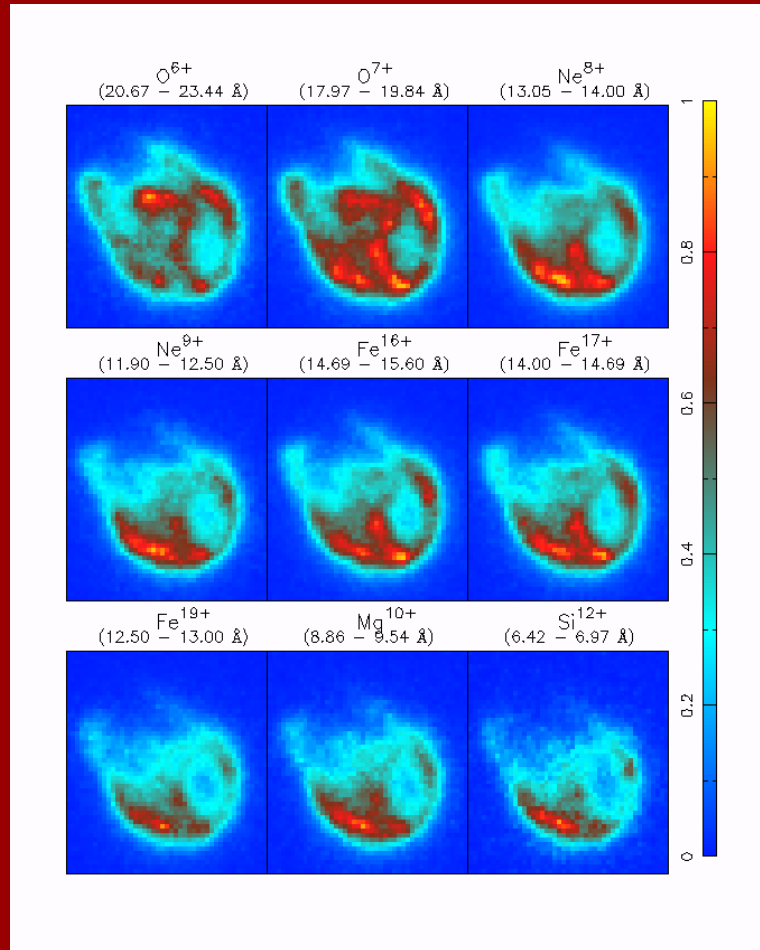


Behar, Rasmussen, Griffiths, et al. 2002

SNR's (cont.): The Magellanic Clouds Sample



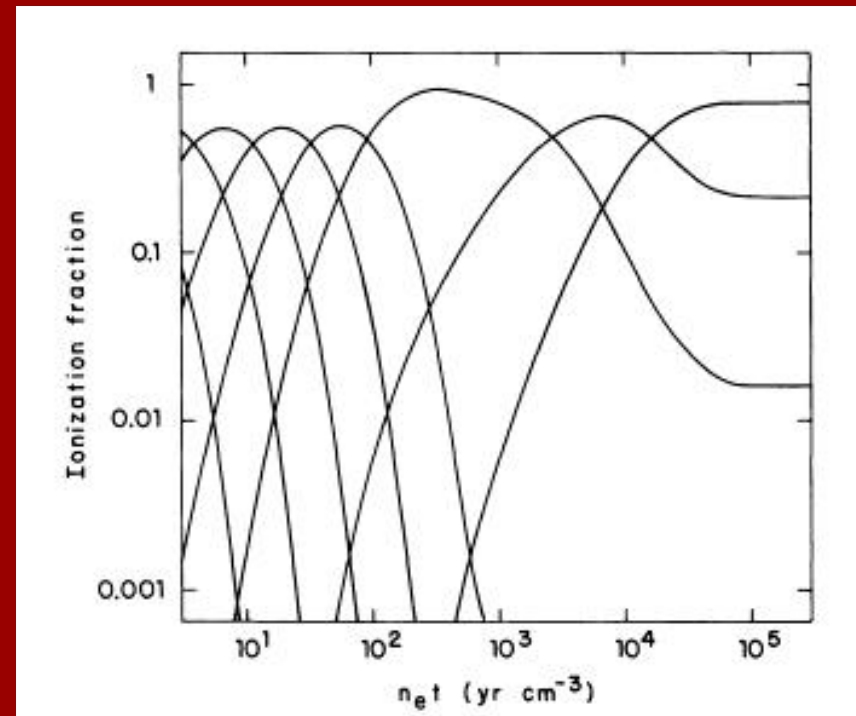
Moderate Resolution CCD's: Complementing the Gratings



**N132D with
XMM-Newton/EPIC-MOS** from
Behar, Rasmussen, Griffiths, et al. 2001

Non-Equilibrium Ionization (NEI)

- ❖ Abrupt heating by shocks together with the low gas density lead to long, progressive ionization
- ❖ NEI Plasma can be expected



Ionization evolution of O at ~ 300 eV
from Hughes & Helfand (1985)

Age Estimate of the Remnant

- ❖ The set of equations needed to be solved:

where the transition matrix T comprises the ionization and recombination rates as a function of $n_e t$:

$$\frac{d}{dt} \begin{pmatrix} n_0 \\ \cdot \\ \cdot \\ \cdot \\ n_Z \end{pmatrix} = \hat{T} \begin{pmatrix} n_0 \\ \cdot \\ \cdot \\ \cdot \\ n_Z \end{pmatrix}$$

- ❖ Together with the emission measure (EM), one can in principle disentangle age (t) from density (n_e)

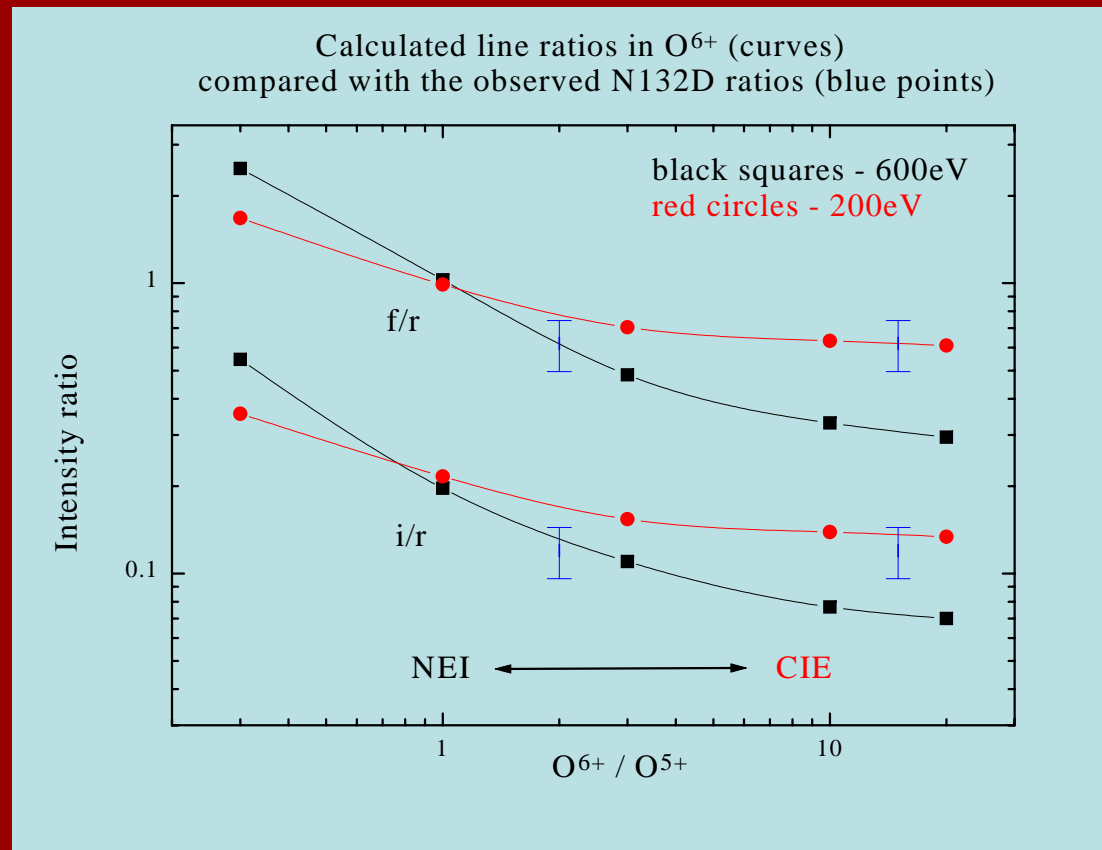
$$EM = n_e n_H V = \frac{4\pi d^2 F_{ji}}{A_{el} f_q(T_e) P_{ji}}$$

Diagnositics with He-like lines (triplets): r , i , and f

❖ $1s^2 - 1s2l$ ($J=1$)
line ratios. We
expected:

- i/r (T_e)
- f/r ($n_e t$)

❖ BUT, problem
turns out to be
degenerate: i also
feeds from inner-
shell ionization



Degeneracy of He-like Lines as NEI Diagnostics

❖ Indeed, models for both

- low- T CIE

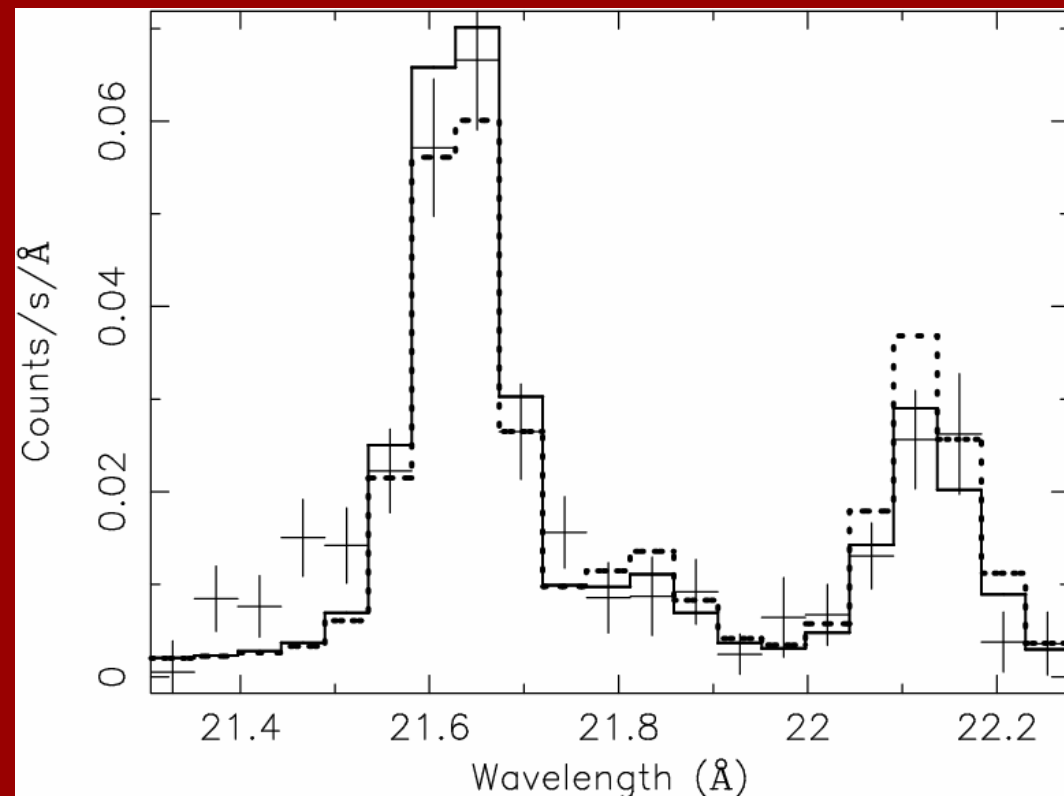
and

- high- T NEI

fit the spectrum equally well

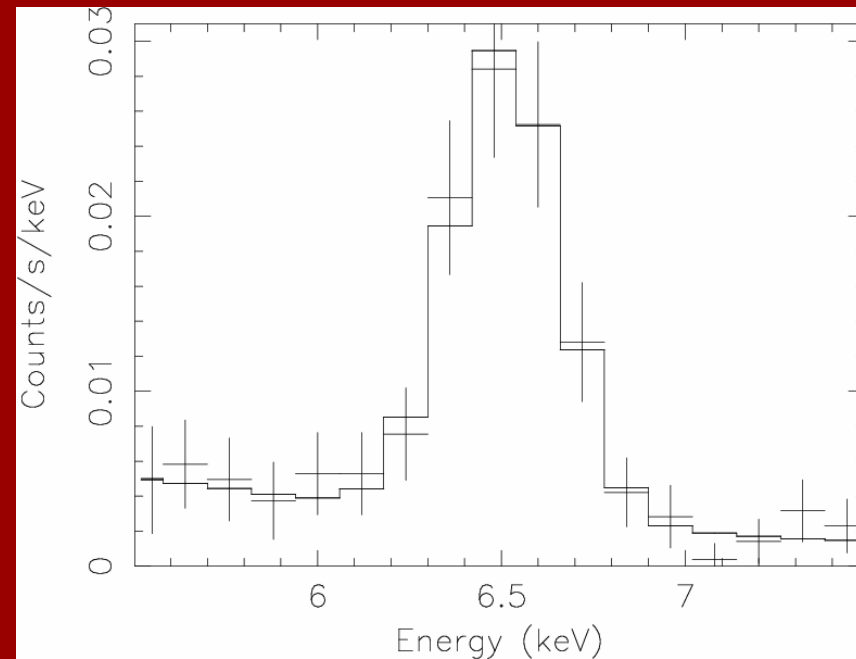
❖ **This plot taken from the RGS spectrum of N103B**

(van der Heyden, Behar, Vink, et al. 2002)



Fe-K for NEI Diagnostics

- ❖ Inner-shell 1s - 2p Fe lines at $E < 6.7$ keV possible only for high- T NEI conditions
- ❖ For N103B we get:
 - Fe^{19+} - Fe^{21+} @ $kT_e = 4$ keV
 - $n_e t = 2000$ yrs cm^{-3}
 - $EM \Rightarrow n_e = 20$ cm^{-3}
- ❖ The hot, Fe-K component is only 100 yrs old: Recently shocked
- ❖ Other plasma components suggest the age of the remnant is 3000 yrs



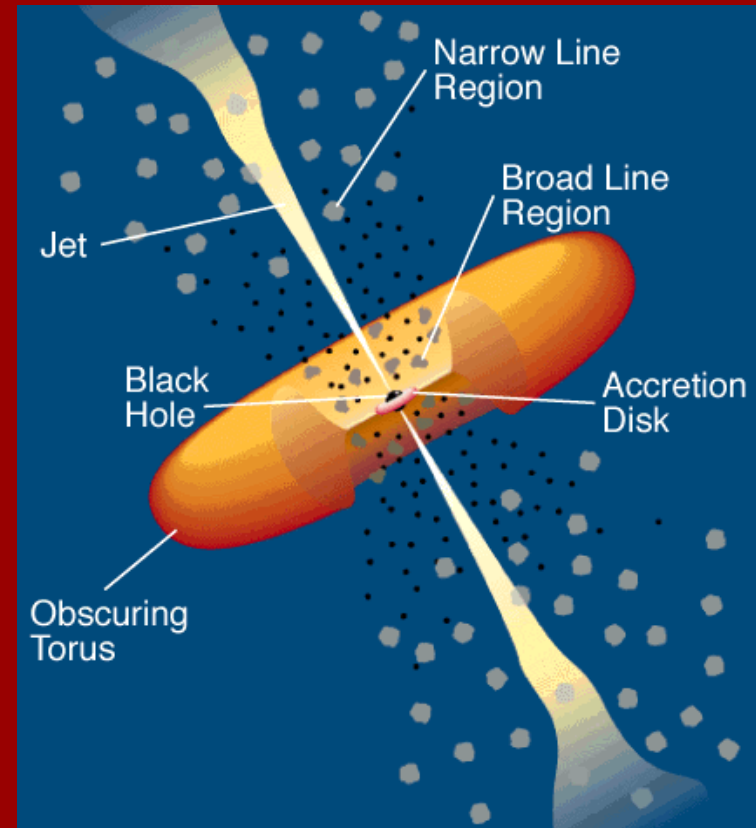
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Active Galactic Nuclei (AGN)

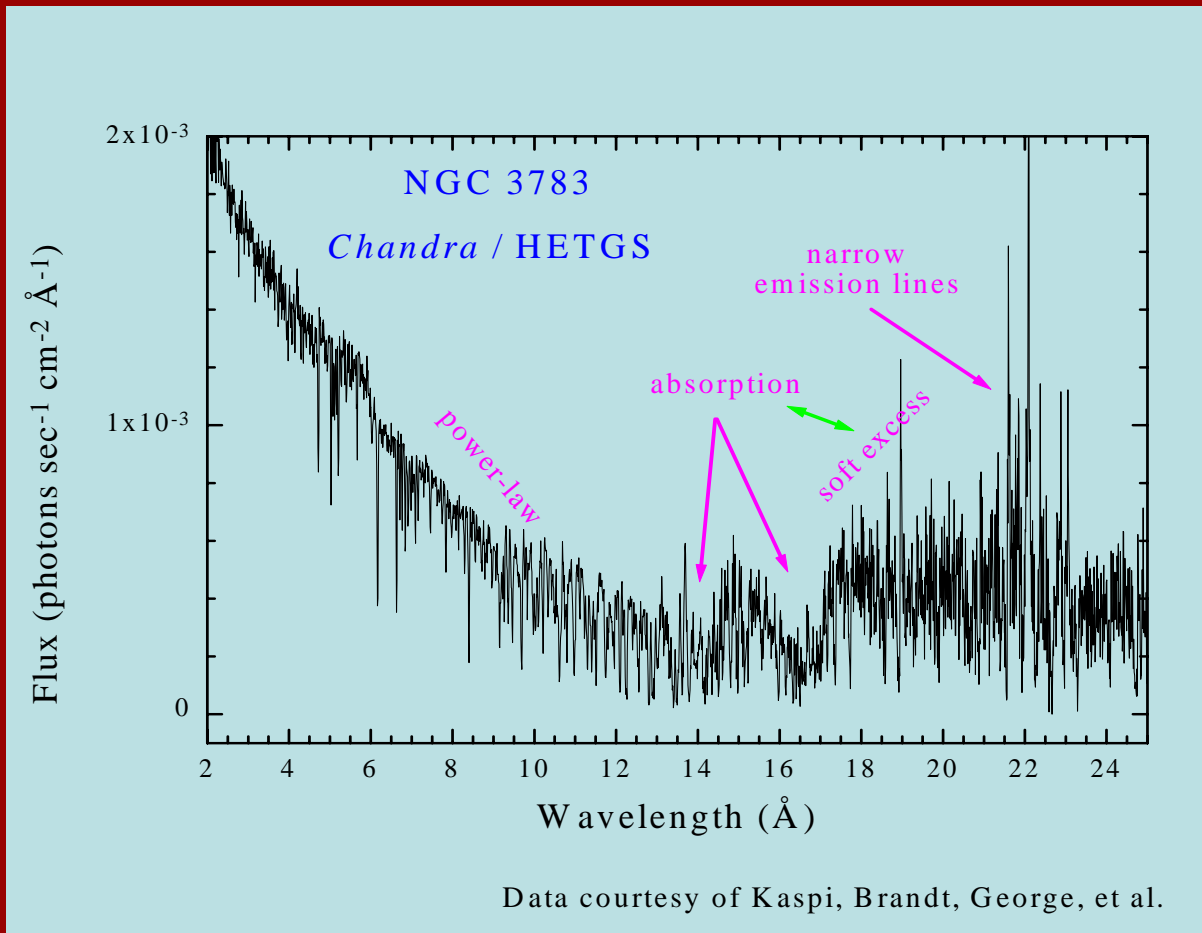
❖ The “Canonincal” Picture of AGN based on UV, optical, and radio observations:

- Central Engine: Supermassive BH
- Accretion through disk
- High-velocity outflows
- Dusty structure (torus):
Gives rise to two “types” of AGN,
depending on observer’s position



Cartoon by Urry and Padovani

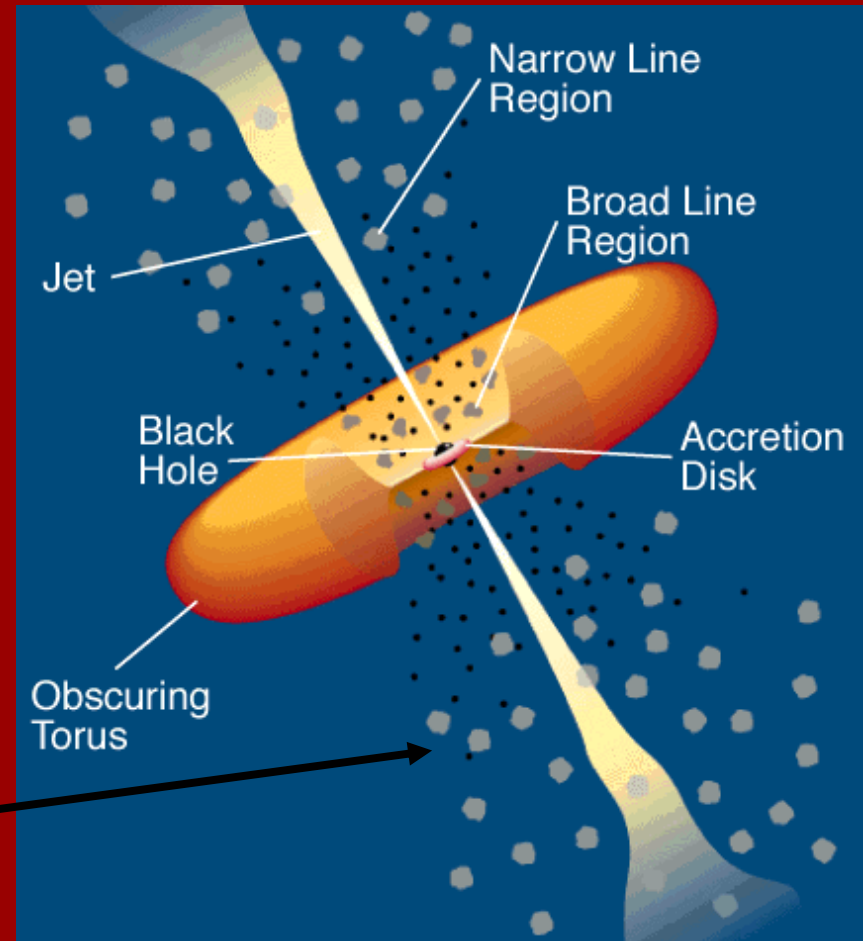
Type-I AGN: Absorbed Continuum



Type II AGN

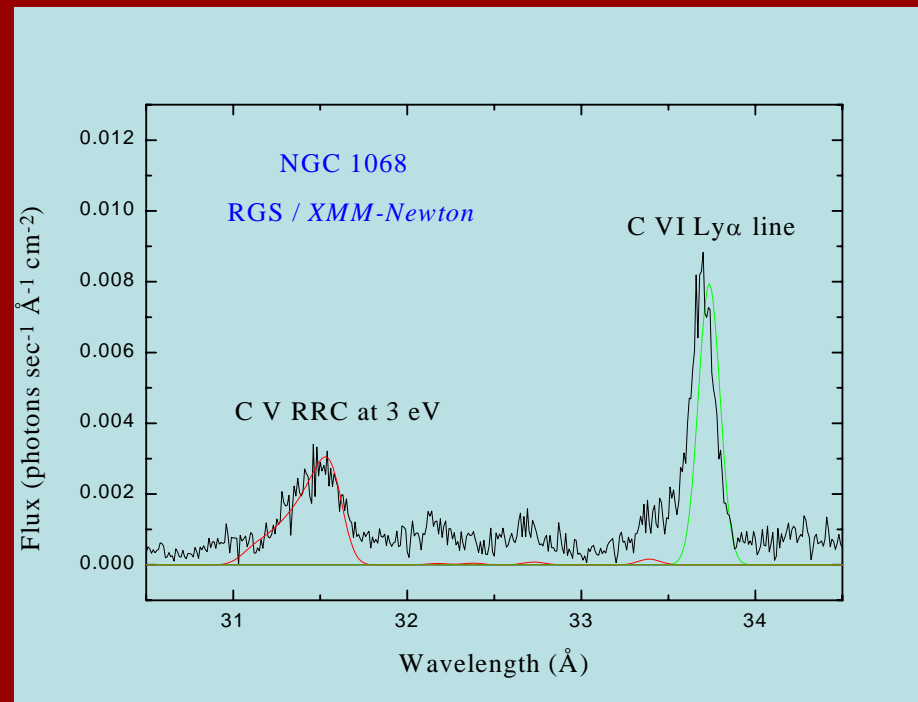
- ❖ Same source (?), but different point of view:

observer



Narrow RRC: The Smoking Gun of Photoionized Plasma

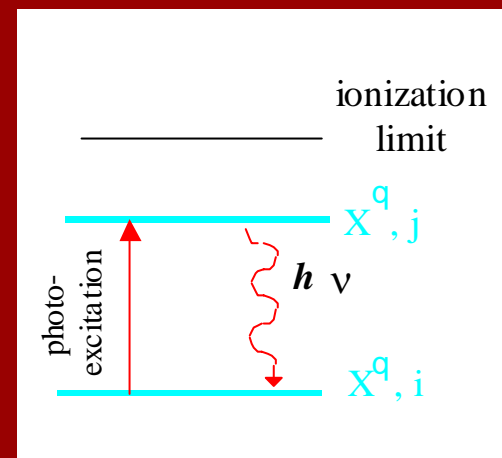
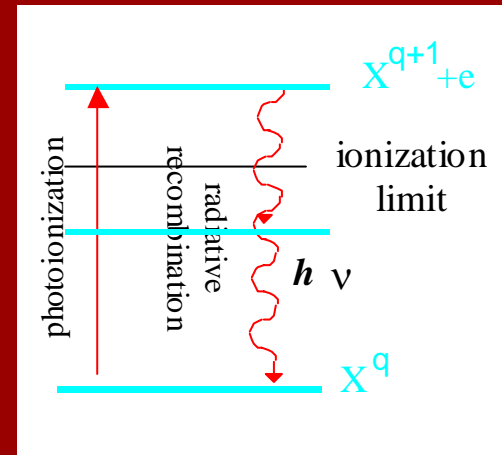
- ❖ Narrow Radiative Recombination Continua (RRCs) resemble emission lines
- ❖ Their shape maps out directly the electron energy distribution (e.g., temperature)
- ❖ Indeed, temps. (kT_e) of a few eV are measured



Photoionized Plasma (cont.): Line Emission Mechanisms

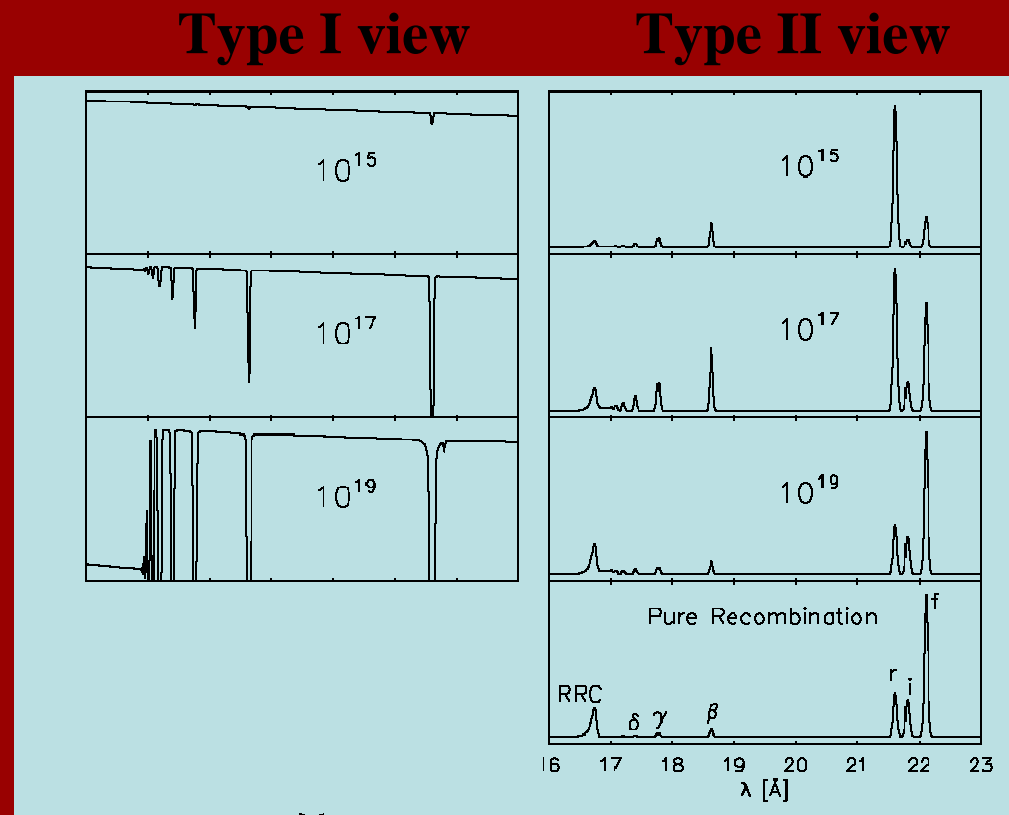
❖ The two basic
line-forming processes:

- Photoionization (PI)
followed by
recombination and
ensuing radiative
cascades
- Photoexcitation (PE)
(resonant scattering)



Measuring Column Density *Perpendicular to the Line of Sight*

- ❖ Line ratios depend strongly on the balance between PI (recombination + cascades) and PE, which in turn, depends directly on the column density (& line width).
- ❖ When the resonance lines saturate, the PE contribution diminishes while PI (recombination) persists.



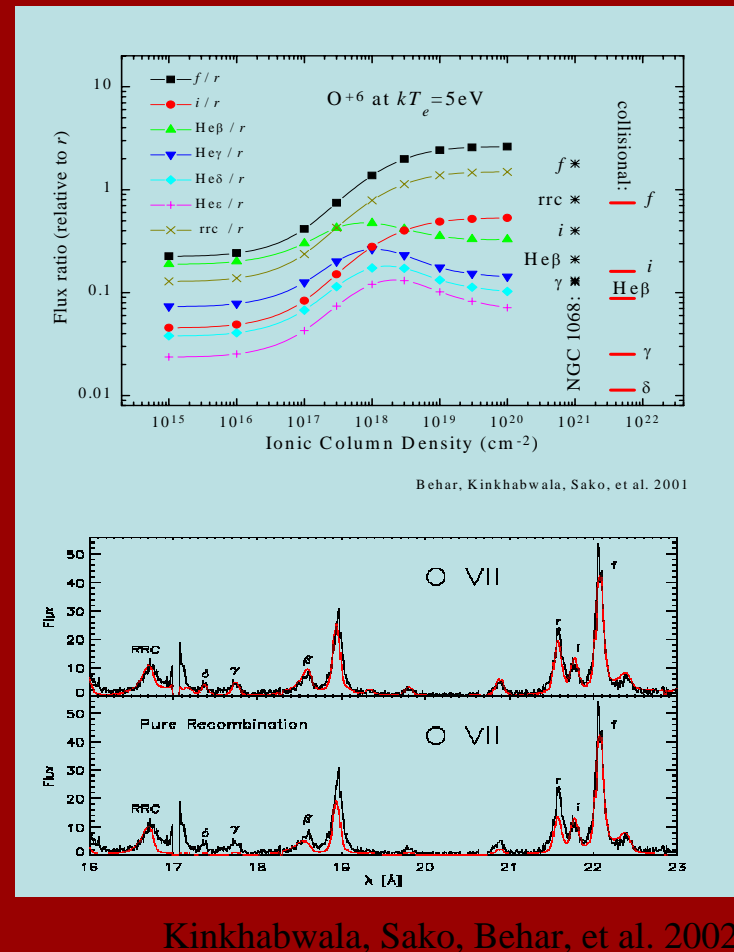
Kinkhabwala, Sako, Behar, et al. 2002

Hot Gas In AGN? Early Confusion

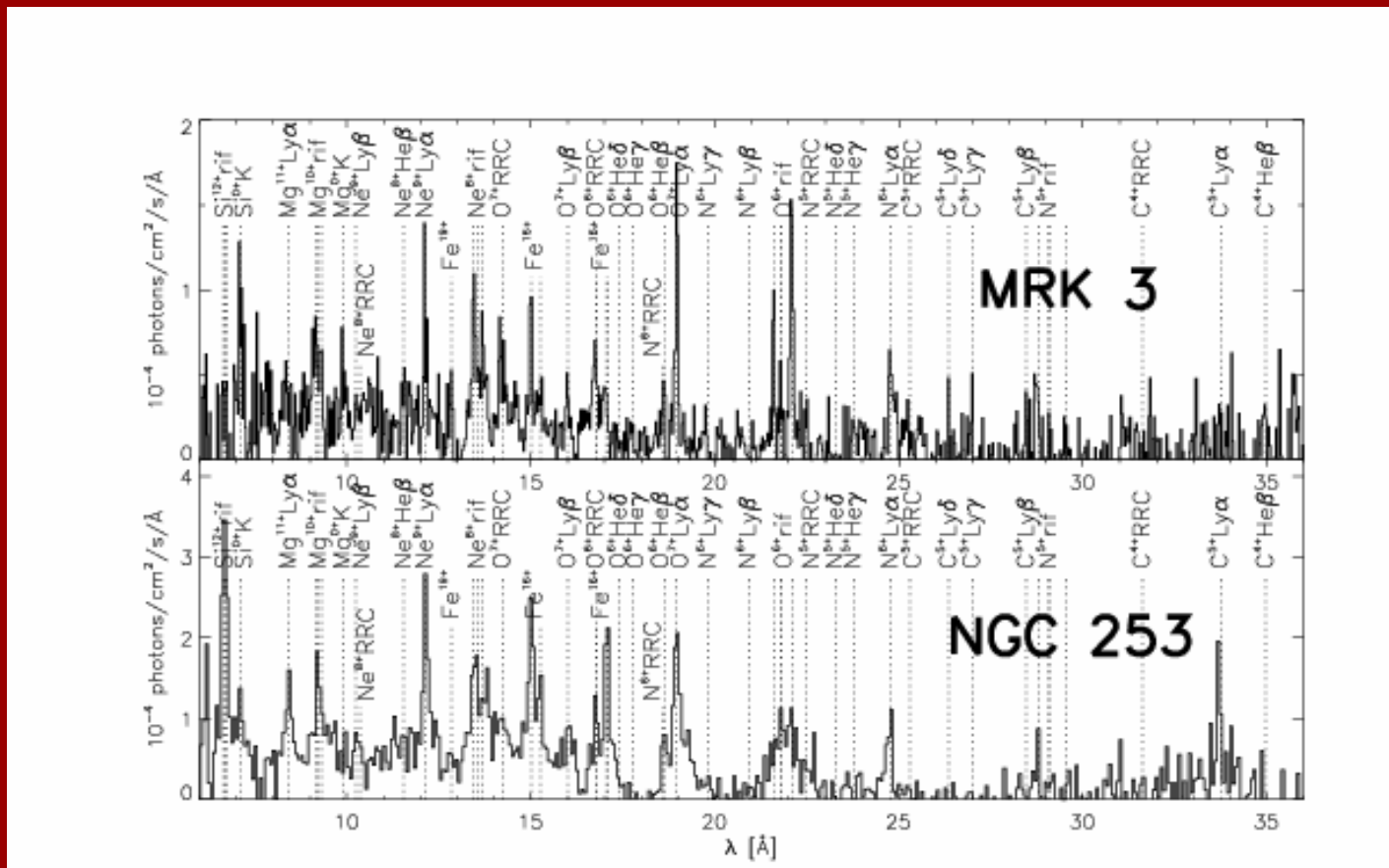
- ❖ The PE effect in the He-like triplets can be somewhat mimicked by hot collisional gas.
- ❖ Early *Chandra* / HETGS paper on NGC 4151 (Ogle et al. 2000) found that the He-like lines do not resemble recombination spectra (Liedahl 1999, Porquet & Dubau 2000).
- ❖ This was taken as evidence for the presence of collisional gas: “*Chandra* data give the first direct evidence for x-ray emission from a hot ($T \sim 10^7$ K) plasma in an AGN system”, which caused confusion in the x-ray community, among other things, in the context of circumnuclear starburst.
- ❖ It is clear now that the He-like triplets alone are insufficient. Fortunately, the high- n lines remove the ambiguity.

Type II AGN: Measuring Column Density (cont.)

- ❖ The high- n lines provide a clear distinction between AGN (PIP) and starburst (CIP).
- ❖ All of the Seyfert 2 x-ray spectra we have looked at so far, namely: NGC 1068, Circinus, NGC 4507, Mkn 3, & NGC 4151 could be explained by pure photoionization models (i.e., no starburst).



AGN vs. Starburst: The X-Ray Side of the Story

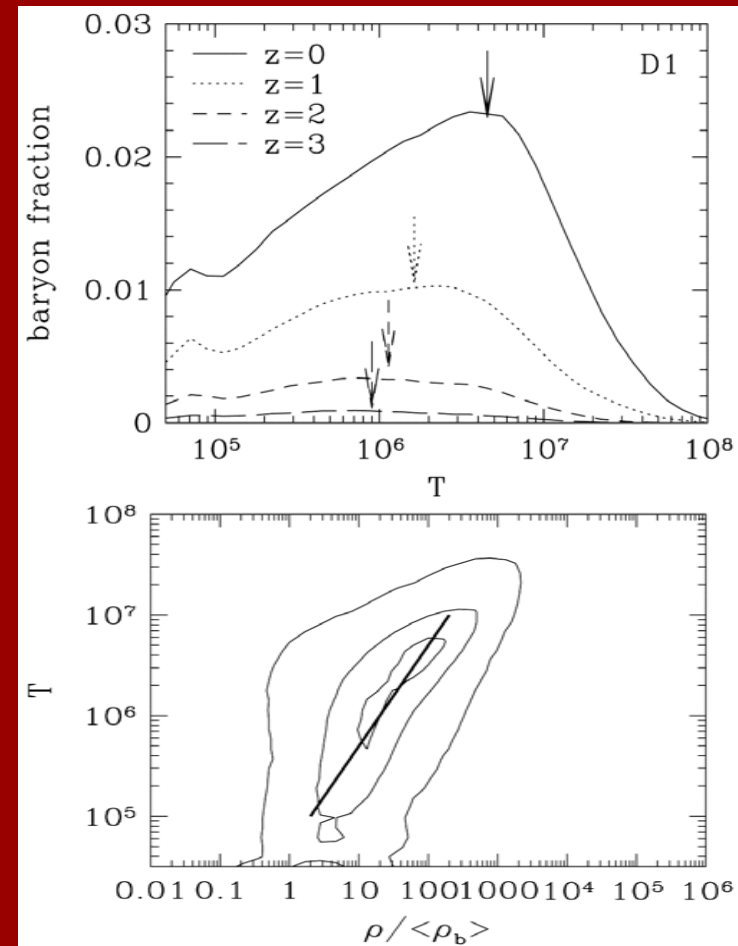


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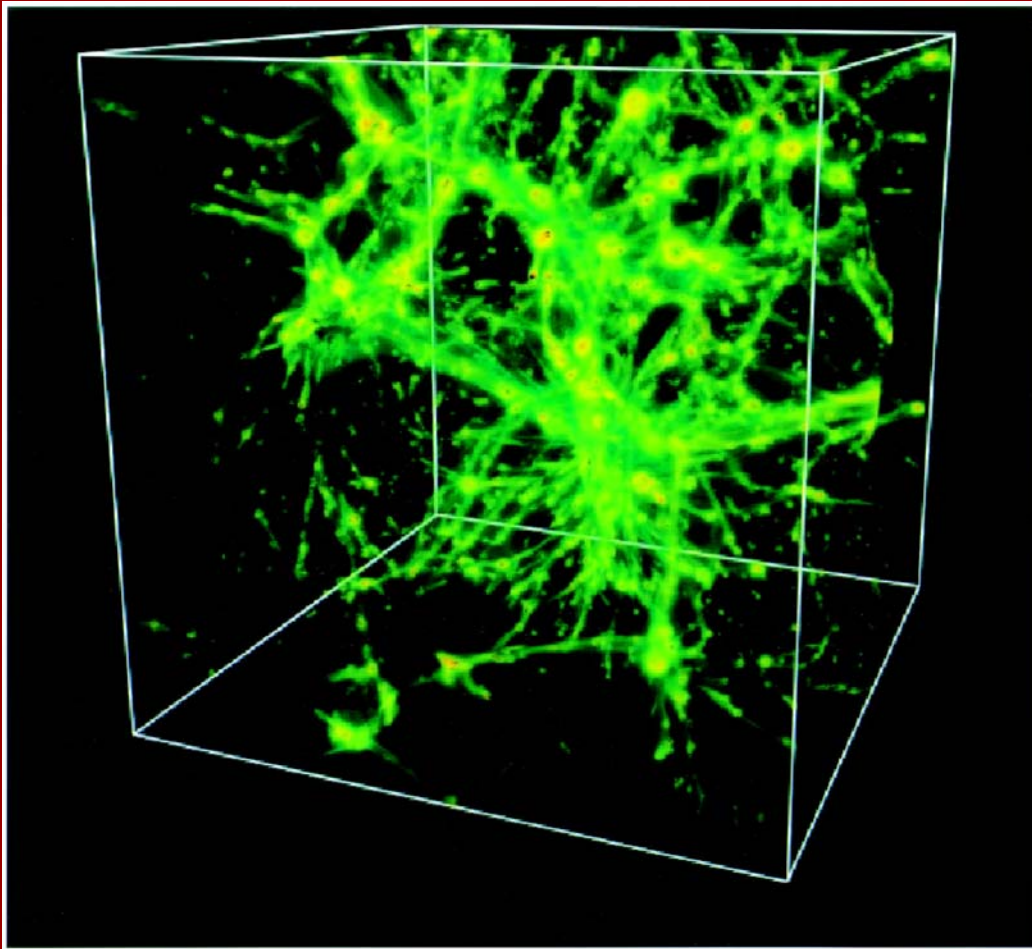
The WHIM: A New Type of Hybrid Plasma?

- ❖ Cosmological simulations show that the majority of baryons in the universe are in the intergalactic medium under warm-hot conditions (WHIM).
- ❖ The WHIM has been heated by gravitational shocks, and remains at extremely low densities.
- ❖ Under these conditions, the gas is neither purely collisional (XRB, low- n) nor purely photoionized (high- T).



Davé, Cen, Ostriker, et al. 2001

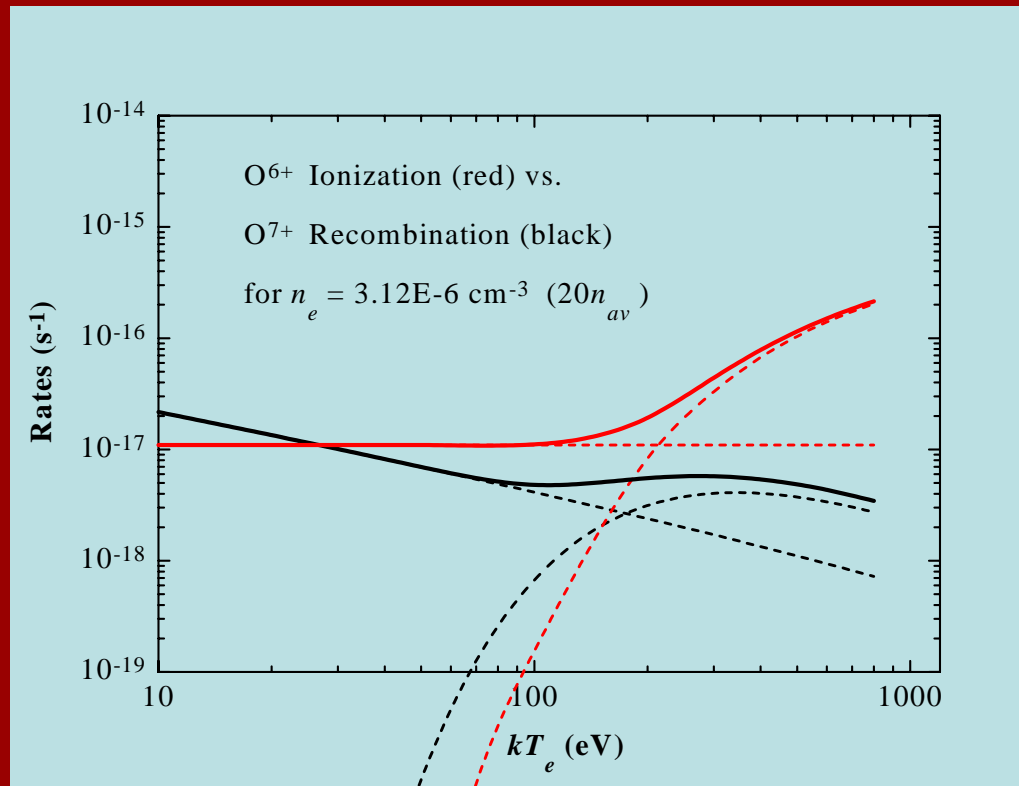
The Cosmic Web



Davé, Cen, Ostriker, et al. 2001

NEI effects in the WHIM

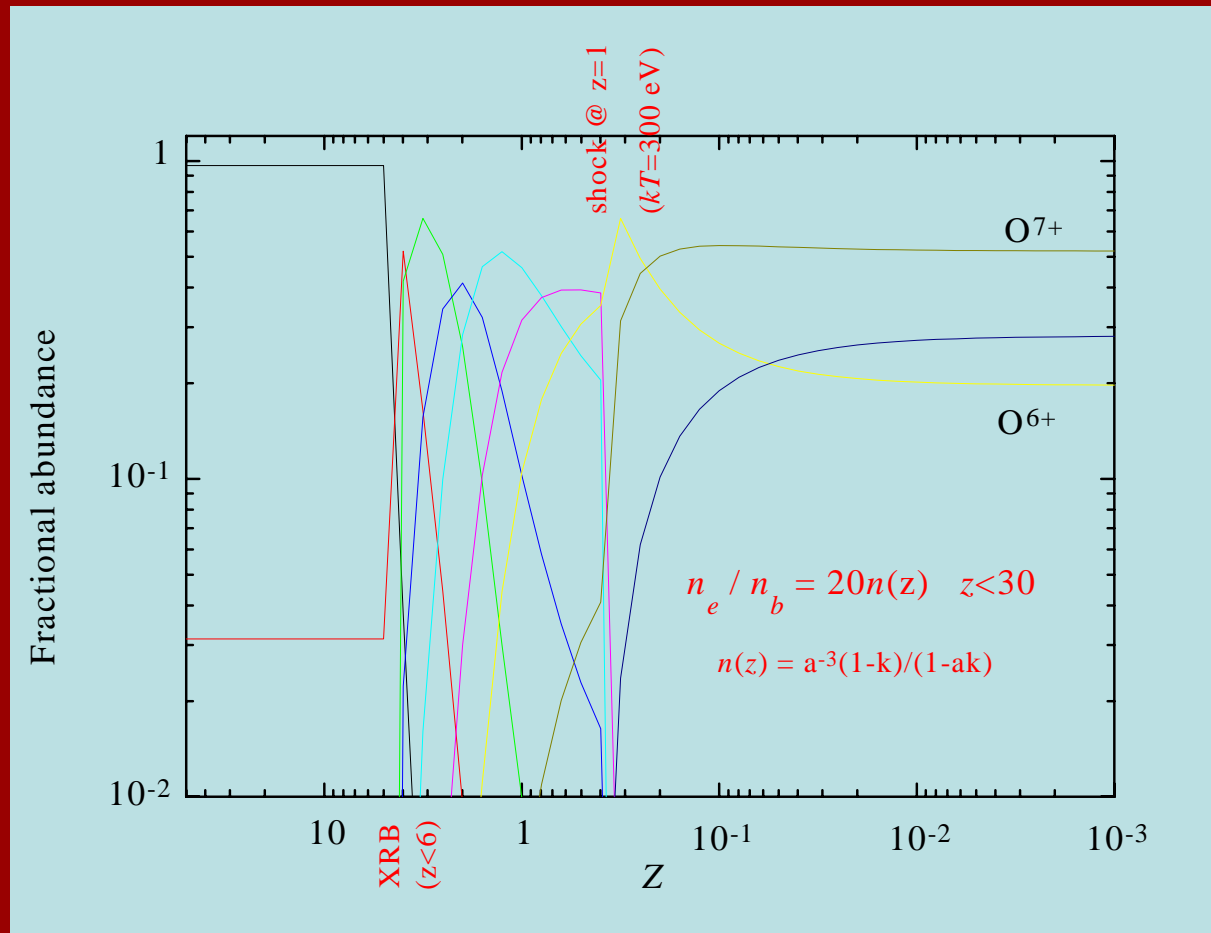
- ❖ At the very low densities, recombination and ionization rates are extremely slow
- ❖ All mechanisms are important
- ❖ Typical times are $\sim 10^{17}$ s = a few billion years



Metal Ionization Evolution of the WHIM: Numerical Problem

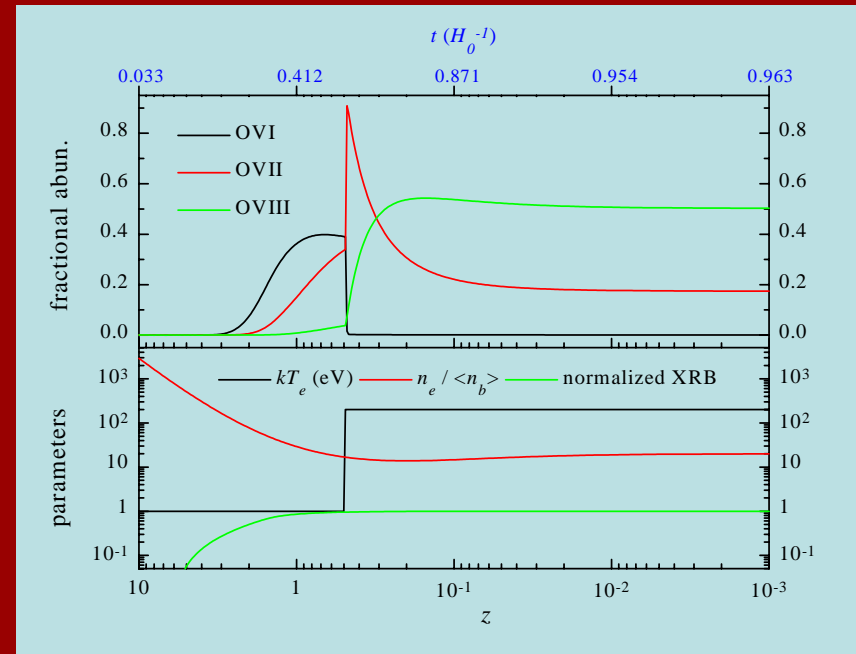
- ❖ The set of linear equations we need to solve is the same as for SNR's: $d/dt(n_i) = Tn_i$, where the transition matrix T includes the ionization and recombination rates: $n_e S_{q,q+1}(T_e)$, $n_e \alpha_{q+1,q}(T_e)$ (i.e., RR+DR), $R^{PI}_{q,q+1}(F_E)$, which are most conveniently taken from Verner, Verner, Ferland (1996) and from Mazzotta, Mazzitelli, Colafrancesco, & Vittorio (1998).
- ❖ When $d/dt(T) = 0$, this set of equations has an analytical solution: Superposition of exponentials.
- ❖ However, for the WHIM, n_e , T_e , and F_E all change with time.
- ❖ Preliminary method: all parameters are taken as step-functions (the steps arbitrarily dense) and within each time bin we solve for a constant T matrix.

WHIM: Plausible Scenario



Highly Ionized O: Possibly Observable

- ❖ Redshifted *absorption* by O VI has been observed in the UV and interpreted as arising from the WHIM.
- ❖ UV SMEX mission SPIDR to study *emission* by WHIM has been approved by NASA.
- ❖ The hot temperatures in the WHIM suggest that its x-ray signature might be detected, although as of yet instrumental limitations are considerable.

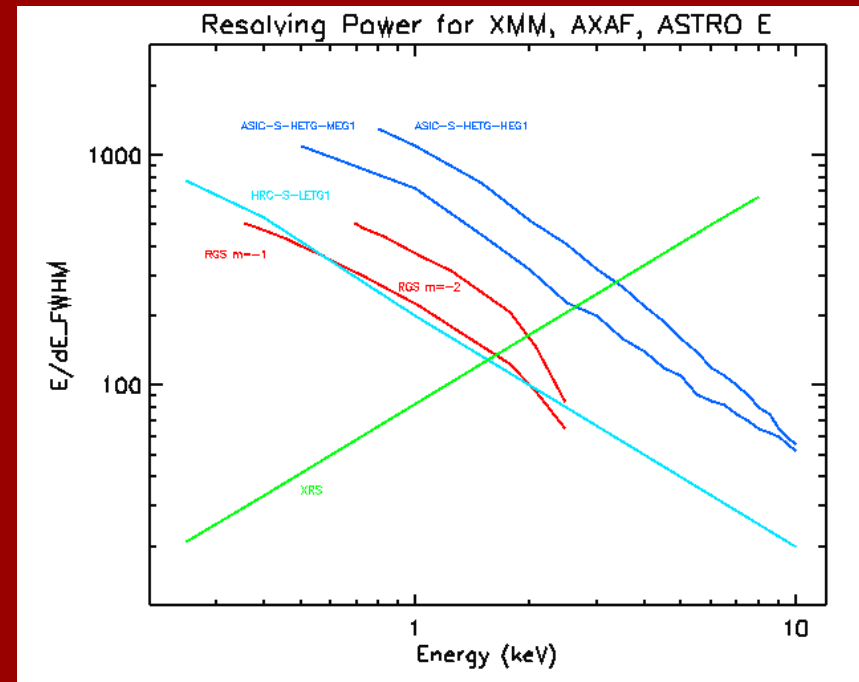
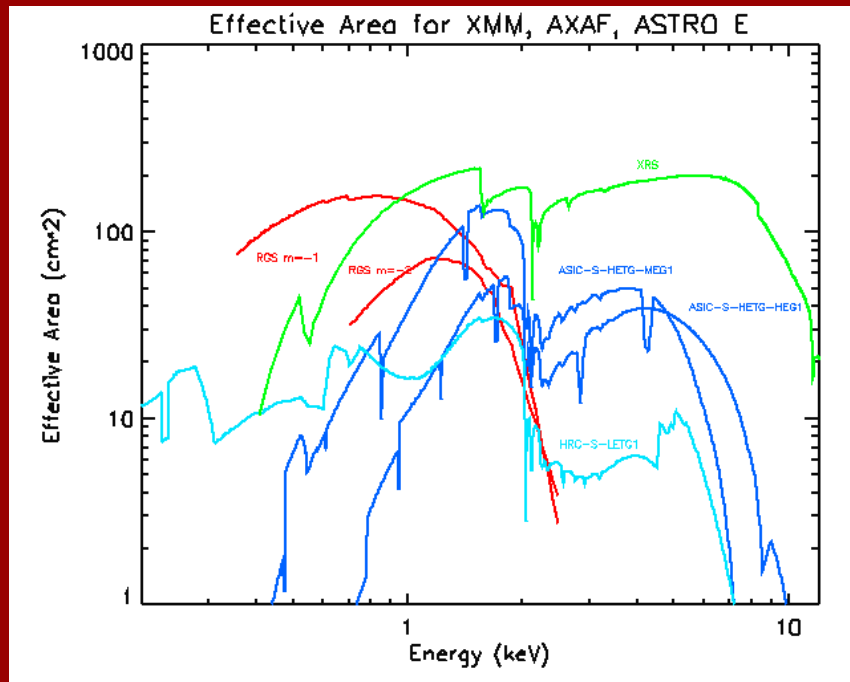


Summary

- ❖ Grating spectra are constantly being obtained with *Chandra* and *XMM-Newton*
- ❖ These have revolutionized the field of X-Ray Astronomy
- ❖ Many x-ray sources are being carefully studied in unprecedented detail
- ❖ SNR's are particularly challenging due to their significant spatial extent
- ❖ Early images and spectra of SNR's confirm the shocked, hot nature of these x-ray sources.
- ❖ NEI effects are sought, but so far only hot Fe-K in NEI has been observed unambiguously
- ❖ A handful of x-ray selected Seyfert 2 sources that have been studied in great detail feature spectra consistent with photoionized gas at intermediate column densities governed by the AGN ionization cone.
- ❖ There is no evidence for collisional gas (i.e., no shocks and no starburst)
- ❖ The WHIM represents a possibly new type of hybrid plasma, in a mixture of collisional and photoionized conditions
- ❖ Spectral modeling of the WHIM is impeded by the variability of essentially all of the physical parameters.
- ❖ Nonetheless, preliminary calculations show that NEI effects could be important

Questions?

Comparison of the Performance Characteristics of the *Chandra* and *XMM-Newton* Spectrometers



The X-Ray

Type-I - Type-II AGN Connection

- ❖ The emitting/absorbing plasmas in both type I and type II AGN seem to feature similar characteristics and physical parameters:
 - Low photoionization temperatures (a few eV)
 - Outflow velocities (up to a few times 100 km/sec)
 - Turbulent (bulk) velocities (a few times 100 km/sec, but also 10,000 km/sec)
 - Column densities ($N_H =$ a few times 10^{21} cm⁻²)
 - Solar elemental abundances (for the most part)
 - No significant x-ray emission by collisional plasma (i.e., no SB)
- ❖ Type I AGN are unique in providing a glimpse at the immediate BH environment
- ❖ All these reinforce the “canonical” unified picture of AGN in the x-rays
- ❖ A BIG question remains regarding the location (density) of the gas:
 - In type II AGN: observed to be extended up to a few 100 light yrs
 - In type I AGN: accurate timing measurements are required
- ❖ Connection to other wavebands is also established through broad and narrow emission lines (BLR and NLR) and also by inner-shell absorption