

Iron photoionized plasma experiments at conditions of x-ray reflection from accretion disks

Roberto C. Mancini
Department of Physics
University of Nevada, Reno

Photoionized plasmas

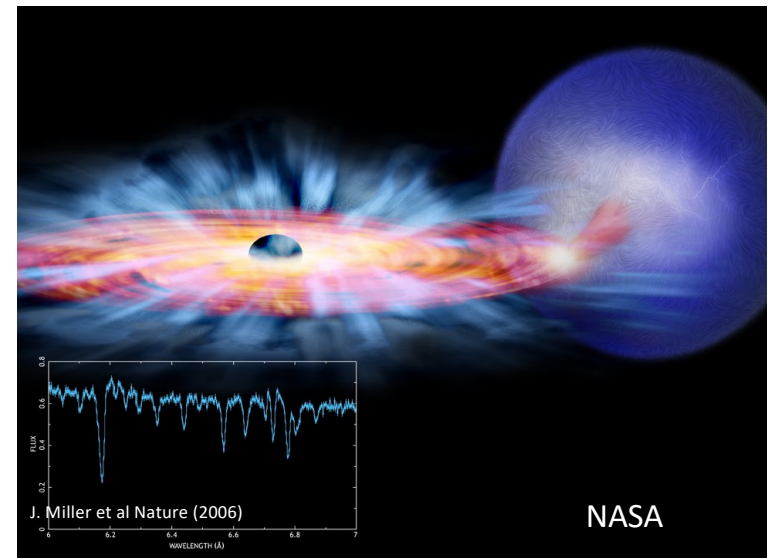
- Widespread in space, e.g. active galactic nuclei warm absorbers, x-ray binaries, accreting disk surrounding black holes
- Plasma is driven by an intense, broadband distribution of photons
- Unlike plasmas produced by a distribution of particles, photoionization and photoexcitation dominate atomic physics and ionization¹
- Understanding photoionized plasmas is relevant to many problems in astrophysics including resonant Auger destruction, thermal instability, and x-ray reflection models

Photoionized plasma in steady state

- Astrophysical photoionized plasma models are employed to interpret x-ray astronomy observations recorded by orbiting telescopes Chandra and XMM-Newton
- They assume photoionization equilibrium (PIE): a steady state in which x-ray flux driven photoionization is balanced by by electron driven radiative and dielectronic recombination²
- **Achieving iron PIE in laboratory experiments requires the energy and x-ray flux duration only available at NIF**

¹R. C. Mancini, J. E. Bailey, T. Kallman et al, Phys. Plasmas **16**, 041001 (2009)

²T. Kallman, Space Science Reviews **157**, 117 (2010)



Artists impression of binary system GRO J1655-40, 11,000 lights years away in constellation Scorpius ²

Astrophysics relevance and impact

- The experiments and measurements of the NIF iron photoionized plasma experiments are relevant to and impact many astrophysics problems
- Uncertainties in modeling of heating and cooling rates play a critical role in the explanation of the disk wind¹
- The analysis of x-ray astronomy observations is not fully consistent and questions about photoionized plasma energy balance and temperature overestimations remain unanswered²
- Interpretation and analysis of iron spectral features from x-ray “reflection” spectrum provides one of the best methods to infer the black hole spin³
- However, the large iron abundances required to fit data remain a puzzle⁴
- Accurate models of plasma charged state distributions are priority level 1⁵

¹Higginbottom et al, *Astrophys. J.* **807**, 107 (2015)

²T. Kallman, M. McCollough et al, *Astrophys. J.* **874**, 51 (2019)

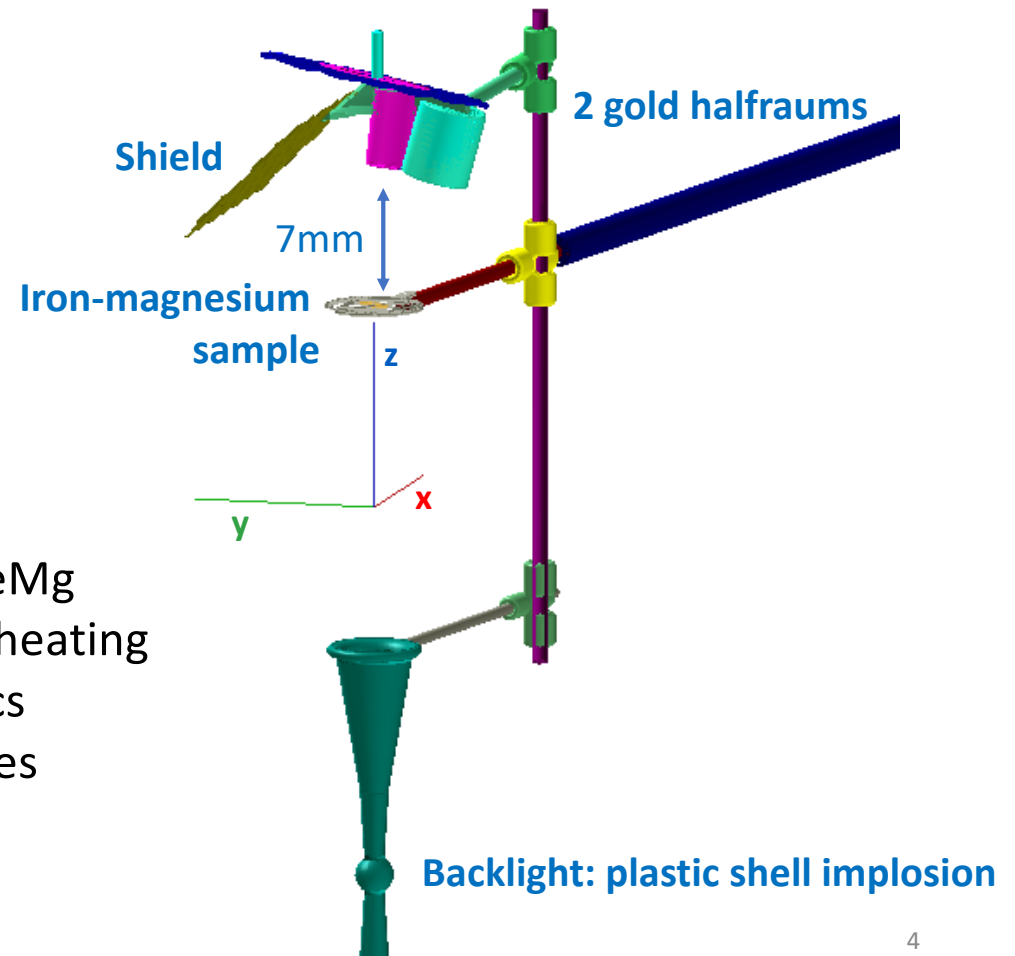
³J. Garcia J., Dauser et al, *Astrophys. J.* **768**, 146 (2013)

⁴J. Garcia and A. C. Fabian et al, *Mon. Not. Royal Astron. Soc.* **462**, 751 (2016)

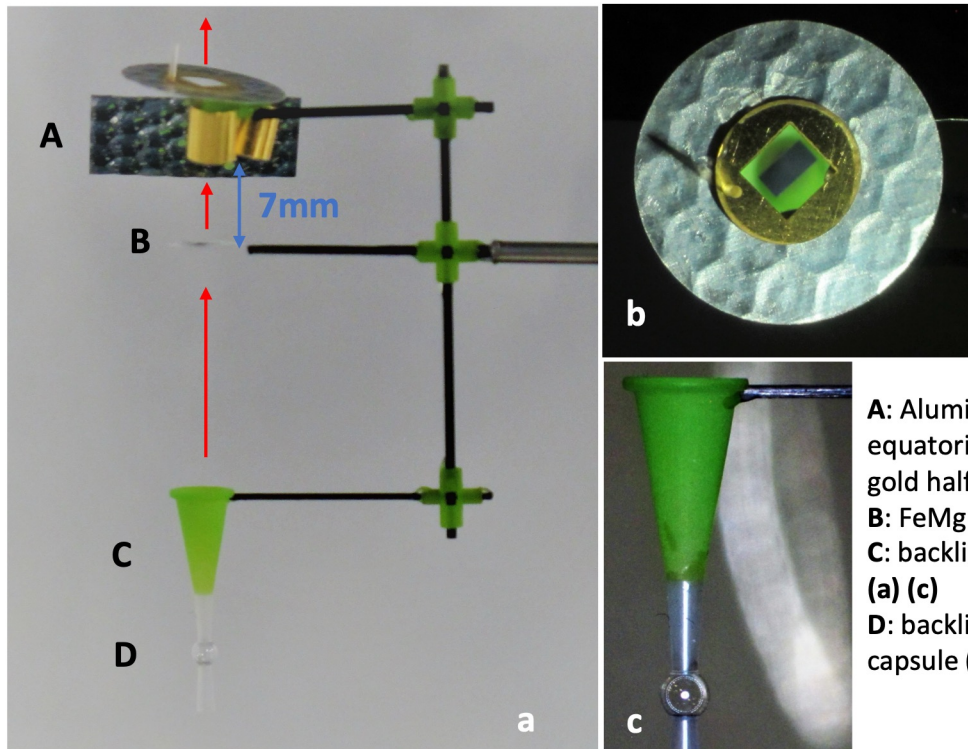
⁵N. Brickhouse, G. Ferland et al, NASA Laboratory Astrophysics Workshop: Scientific Organizing Committee Report, *BAAS* **52**, 0202 (2020)

Schematic of NIF photoionized plasma experiment: **Photoion**

- Three component set up along polar z-axis:
 - X-ray Source: 2 gold halfraums
 - Sample: iron-magnesium comix
 - X-ray Backlight: capsule implosion
- Drive halfraums sequentially in time, i.e., back-to-back, to produce a steady x-ray drive of up to 12ns duration
- The halfraum x-ray flux into the tamped FeMg sample drives a controlled expansion and heating so that photoionized plasma atomic physics evolves through a sequence of steady states
- Measure drive, sample expansion, and transmission & self-emission spectra

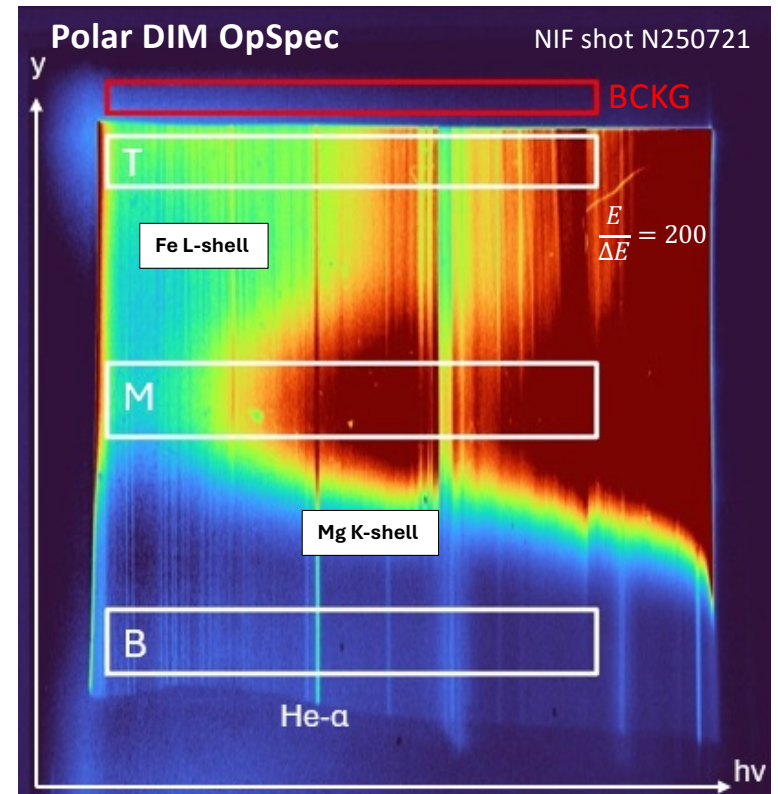


NIF experiment set up and OpSpec image data



A: Aluminum shield for equatorial OpSpec and gold halfraums **(a)**
B: FeMg sample **(a) (b)**
C: backlighter collimator **(a) (c)**
D: backlighter implosion capsule **(a) (c)**

Example of FeMg tamped sample:
 0.5microns CH | $3 \times 10^{18} \text{cm}^{-2}$ Fe + $4 \times 10^{18} \text{cm}^{-2}$ Mg | 0.5microns CH

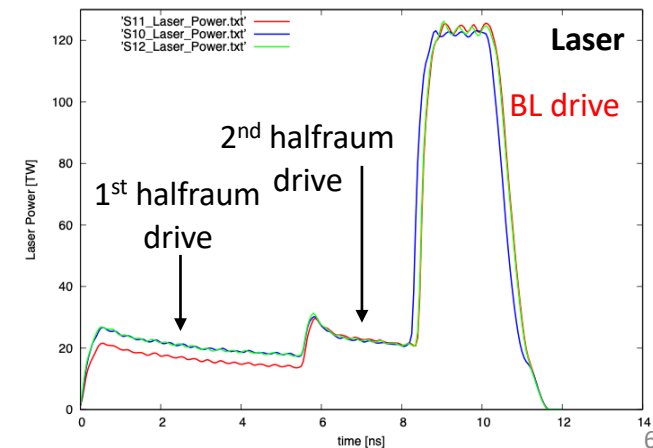
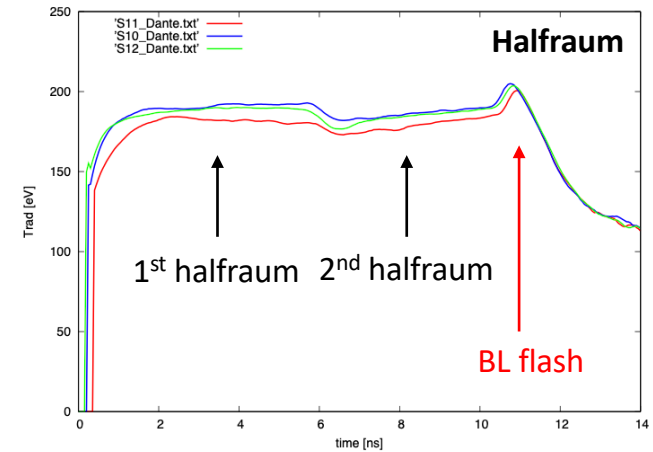


T (top): backlighter transmission through FeMg sample
M (middle): unattenuated backlighter
B (bottom): FeMg sample self-emission

Laser beams and halfraum radiation temperature

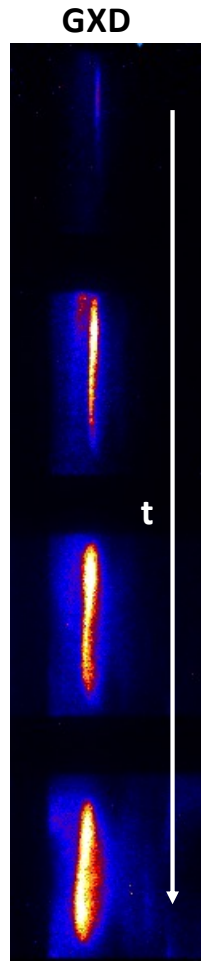
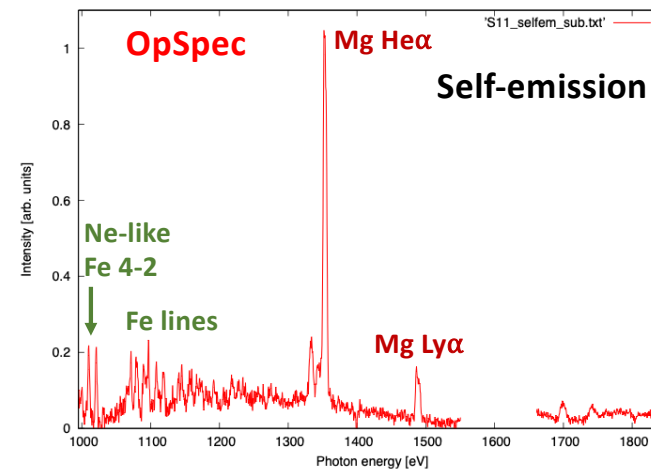
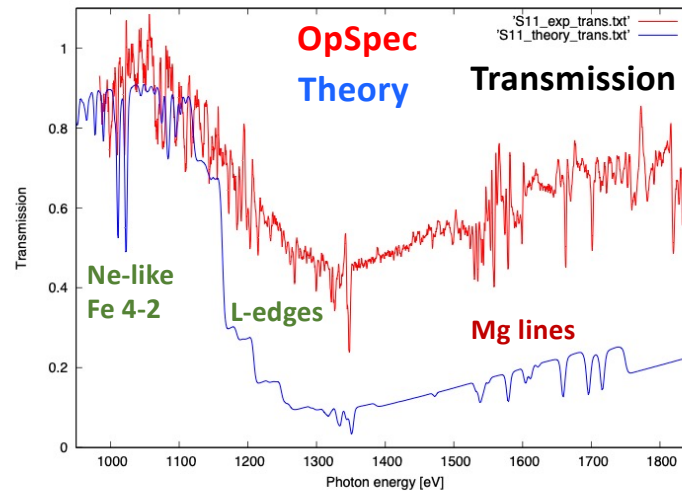
Halfraum $T_{\text{rad}}(t)$ measured with DANTE in July 2025 shots S10, S11 and S12

- 104 NIF laser beams drive halfraums & capsule
- Two gold halfraum x-ray source driven by a total of 40 laser beams delivering 240kJ of UV energy
- Each halfraum is driven by 5 quads
- Halfraums driven sequentially in time, back-to-back, to produce x-ray drive lasting 12ns
- Each laser beam has up to 6kJ of UV energy, peak power of 1.35TW
- Implosion backlighter driven by 64 laser beams with 3.5kJ of UV energy and 1.6 TW of power per laser beam, in a 2.2ns square pulse shape.
- Total UV laser energy for backlighter is 225kJ
- Geometric dilution at the FeMg sample: 5%



Polar OpSpec and equatorial GXD observations

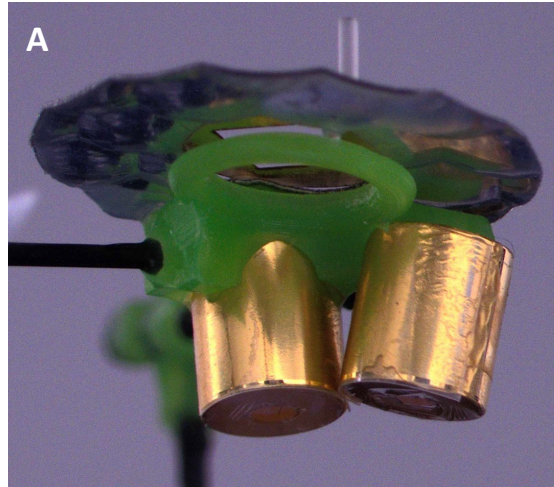
- Main diagnostics: **Dante**, **OpSpec**, **GXD**
- **Dante**: time-resolved x-ray drive (radiation temperature and flux into sample)
- **Polar OpSpec**: KAP crystal, FeMg transmission and self-emission
 - Previous exp: time-integrated
 - Proposed exp: time-resolved (gated)
 - **OpSpecTR**: commissioned in FY25
 - Resolving power $\frac{\lambda}{\Delta\lambda} = 350$ (prior 200)
- **Equatorial GXD** on DIM (90,124): gated slit imager measures sample expansion & plasma density at 4 times
- Secondary OpSpec on DIM (90,78) measures time-integrated FeMg self-emission



Target requirements and components

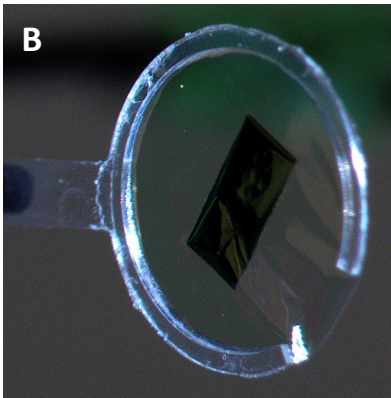
A: X-Ray Source: 2 Gold Halfraums

- 4mm long by 3.5mm diameter
- 50microns thick wall
- Filled with 4mg/cc GACH foam (same as prior experiments)



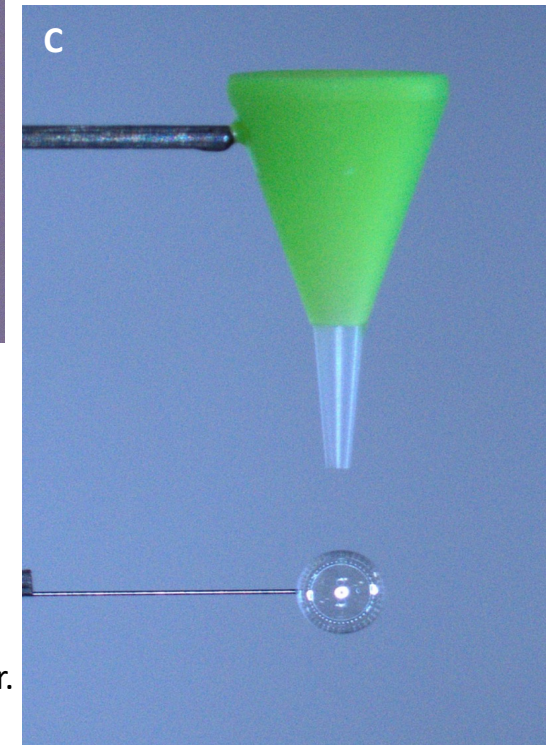
B: Iron-Magnesium Comix Sample

- 2.4mm by 1.2mm FeMg comix samples
- Tamped with 0.5microns or 1.0microns CH,
- Mg areal density in range $2e18$ to $4e18$ cm^{-2}
- Fe areal density in range $5e17$ to $2e18$ cm^{-2}



C: Backlight: Plastic capsule

- 2mm diameter,
- 20microns wall thickness
- with “detached cone” collimator. (same as prior experiments)



Shots and experimental plan

- Previous work at Z has demonstrated the importance of looking at trends^{1,2}
- Experience has shown NIF can efficiently do 3 Photoion experiments per shot-day
- Proposed exp: 1 shot-day in FY27 and 1 shot-day in FY28, which represent 6 more Photoion experiments
- Goal: measure 2 points in x-ray flux/plasma density parameter space
- Why: x-ray flux and plasma density control photon- (ionization) and collision- (recombination) driven atomic processes
- Each point in parameter space requires:
 - 2 back-to-back shots to test steady-state condition and reproducibility
 - 1 shot for calibrations
 - Total of 3 shots (1 shot-day) to establish a point in parameter space

¹D. C. Mayes, R. C. Mancini, T. E. Locakrd et al, Physical Review E, **104**, 035202 (2021)

²J. J. Rowland, R. C. Mancini, G. S. Jaar et al, Astrophysical Journal **995**, 23 (2025)

Team of collaborators

- PI: Roberto Mancini, UNR, experiment design, modeling, and data analysis
- Annabelle Peterson, UNR: PhD graduate student, exp design, modeling, and data analysis
- Liaison Scientist and Co-PI: Robert Heeter, LLNL, NIF experiments
- Rich London, LLNL: Lasnex and Hydra radiation hydrodynamics simulations
- Kathy Opachich, LLNL: Dante measurements, halfraum radiation temperature
- Matthias Hohemberger, LLNL: GXD expansion measurements, plasma density
- Patty Cho, LLNL: NIF experiments, photoionized plasma experiments
- Ted Perry, LANL: NIF experiments, OPSPEC x-ray spectrometer
- Heather Johns, LANL: NIF experiments
- Duane Liedahl, LLNL: atomic physics and Monte Carlo radiation transport
- Tim Kallman, NASA: astrophysicist, modeling with astrophysical code XSTAR
- Javier Garcia, NASA: astrophysicist, x-ray reflection astrophysical models
- Gary Ferland, U. Kentucky: astrophysicist, modeling with astrophysical code Cloudy
- Steve Rose, Imperial College London, UK: atomic physics, modeling with Galaxy code
- Ehud Behar, Technion, Israel: X-ray astronomer, data analysis and interpretation