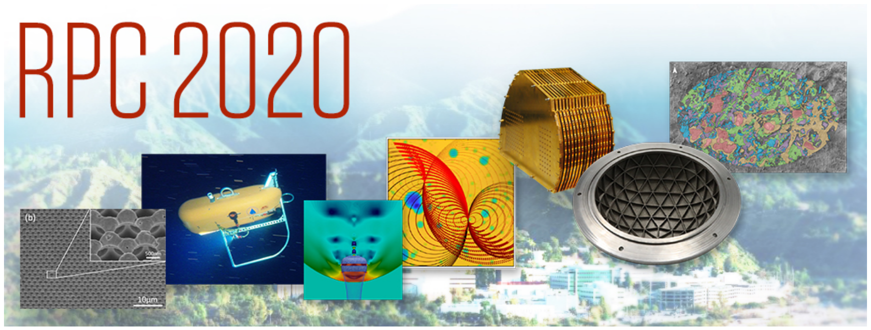

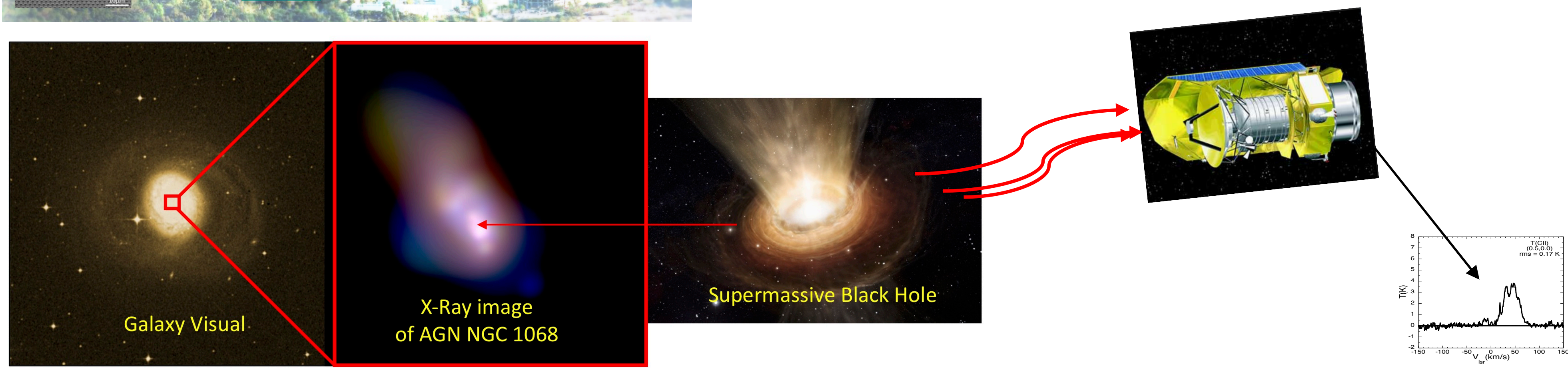

Virtual Research Presentation Conference

Supermassive Black Holes and the X-Ray to Far-IR Connection

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Program: Topic

Assigned Presentation #RPC-012

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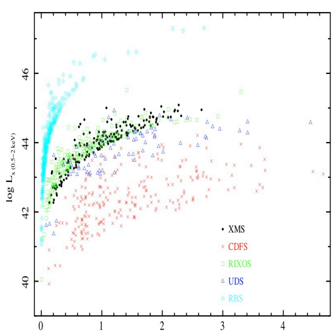
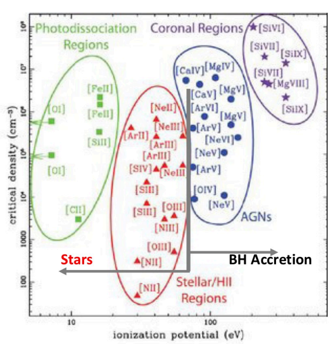
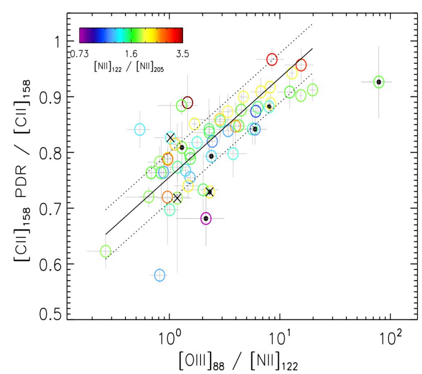
Tutorial Introduction

Abstract

Supermassive black holes in galactic nuclei are among the most luminous sources of radiation within galaxies, emitting nearly all their energy at UV and X-ray wavelengths [1]. This radiation is absorbed by gas and dust in the galactic nucleus, depositing energy, ionizing atoms, and heating the gas. This energy is re-emitted by atoms, ions, and dust, as far- and mid-infrared radiation, most prominently in Luminous- and Ultraluminous Infrared Galaxies (ULIRGs) with Active Galactic Nuclei (AGN). The infrared emission lines of metal ions are important diagnostics of the conditions in these regions (Table 1) and, due to atmospheric absorption, must be observed from orbital or sub-orbital platforms. To interpret this emission we need models of the ionization states of the atoms and ions and model their radiative (emission) signatures. This RTD proposed to develop such a model for the carbon, nitrogen, and oxygen ions to aid interpretation of existing and upcoming observations, as well as to provide support for proposing for an upgraded version to include all important tracer ions .







(left) Soft X-ray luminosity for more than a thousand AGNs with billion solar mass supermassive black holes versus red shift z [1]. These AGNs have X-ray luminosities up to 10 billion times that of the Milky Way's relatively low million solar mass black hole. (center) Illustration of ionization states and their far- and mid-infrared spectral lines as applied to studying different astrophysical phenomena. (right) Representative FIR line study of AGNs [7] showing the ionized carbon [CII] emission versus the ratio of doubly ionized oxygen [OIII] to singly ionized nitrogen [NII], a measure of the hardness of the UV and X-ray radiation fields.

Problem Description

a) The discovery by infrared satellites over recent decades of extremely luminous infrared galaxies and their association with supermassive black holes (SMBH), has opened up a new opportunity to understand the influence of supermassive black holes on galactic evolution over cosmic time.

b) The current state-of-the-art models of conditions in galactic nuclei near sources of intense X-rays [3 -5] do not calculate all the ionization states nor their FIR and MIR spectral lines, and thus are inadequate for interpreting their emission. CLOUDY [6] is the closest code to our proposed model, but is better suited to study the influence of UV on galactic nuclei. The proposed code solves the effects of high luminosity X-rays on Active Galactic Nuclei (X-AGN).

c) Relevance to NASA and JPL: Far-infrared (FIR) and Mid-Infrared radiation carries information active galactic nuclei the supermassive black holes at their center (Table 1). However, this radiation is unobservable from ground based telescopes and so such studies are the provenance of JPL and NASA. We need numerical models to interpret FIR observations of AGNs made with NASA orbital and sub-orbital instruments and telescopes. The model developed under this RTD will assist in such interpretation and to guide requirements for future instruments and missions.

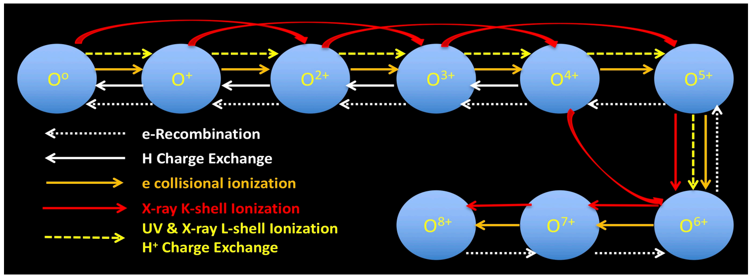
Line Ratio	Diagnostic	Parameter range
[N II]$_{205/122}$	Density of ionized gas	1–10^3 cm^{-3}
[O III]$_{88/52}$	Density of ionized gas	10–$10^{4.5}$ cm^{-3}
[S III]$_{33.5/18.7}$	Density of ionized gas	10–10^5 cm^{-3}
[Ne V]$_{24.3/14.3}$	Density of ionized gas	100–10^6 cm^{-3}
[S IV]$_{10.5}$/[S III]$_{18.7}$	Ionization parameter	34.8–23.3 eV
[O III]$_{88}$/[O I]$_{63}$	Ionized/neutral gas ratio	···
[O III]$_{88}$/[N II]$_{122}$	Ionization parameter	35.1–14.5 eV
[Ne III]$_{15.6}$/[Ne II]$_{12.8}$	Ionization parameter	41.0–21.6 eV
[O IV]$_{25.9}$/[O III]$_{88}$	Ionization parameter, AGN/Starburst	54.9–35.1 eV
[O I]$_{145/63}$	Temperature of neutral gas (PDR)	100–400 K
[C I]$_{609/371}$	Temperature of neutral gas (PDR)	20–100 K
[C II]$_{158}$/[O I]$_{63}$	PDR density	···
[C II]$_{158}$/[N II]$_{122}$	PDR/low-excitation ionized gas contribution	···
[N II]$_{122}$/[C I]$_{371}$	Low-excitation ionized gas/neutral gas contribution	···
[N II]$_{122}$/[C I]$_{371}$	Low-excitation ionized gas/neutral gas contribution	···
[O IV]$_{25.9}$/[Ne II]$_{12.8}$	AGN/Starburst contribution	···
[O IV]$_{25.9}$/([Ne II]$_{12.8}$+[Ne III]$_{15.6}$)	AGN/Starburst contribution	···
[O III]$_{88}$/[N III]$_{57}$	Ionization parameter and metallicity	35.1–29.6 eV
([Ne II]$_{12.8}$ + [Ne III]$_{15.6}$)/([S III]$_{18.7}$ + [S IV]$_{10.5}$)	Metallicity	~0.07–2.5 $Z_\odot$

Table 1. A list of ionized gas parameters that can be derived from the ratios of fine-structure far- and mid-infrared lines, including electron density, radiation field hardness, metallicity, and relative contribution of active galactic nucleus starburst (adapted from Table 2 in [10]). The numbers attached to each atomic label are the corresponding fine-structure line wavelengths (rounded off to a whole number). The term ionization parameter is a measure of the ionizing flux.

Methodology

a) There are six basic steps to model the Far- and Mid-IR spectral line emission from atomic ions in the presence of a strong X-ray source [8,9]. **1) Atomic processes**: Assemble a database of: (i) X-ray K- and L-shell and UV L-shell photoionization (ii) electron and proton collisional processes (see example below); **2) Ionization Models:** Implement a reaction balance code that includes all the ionization states and atomic processes for carbon, nitrogen, and oxygen, and can be extended to any metal. 3) **Radiative Transfer:** Implement a radiative transfer code for the fine-structure emission lines of C, C^+, N^+, N^{++}, O, O^{++}, and O^{+++}; 4**) Far-IR and Mid-IR Emission:** Model the Far-IR and Mid-IR spectral signatures of AGNs, ULIRGs, and LIRGs, in a 1-D model, and vary the input parameters of supermassive black hole X-ray luminosities; **Observational Data Base**: Assemble a representative set of observations of active galactic nuclei from archival databases for FIR and MIR emission lines and X-ray luminosities.

b) This model's innovation is that it focuses on the high ionization states of trace metals in galactic nuclei in the presence of large X-ray and UV fluxes arising from supermassive black holes. It calculates the balance among all ionization states from neutral atoms to fully stripped ions using a closed analytic solution we derived to solve the ion balance equations [8]. It is flexible enough to accommodate any future metal or noble gas atoms of interest. It is a 1-D spherically symmetric model that includes attenuation of the central SMBH X-ray radiation throughout the galactic nucleus. It incorporates a radiative transfer model to calculate the emission signatures of the AGN.



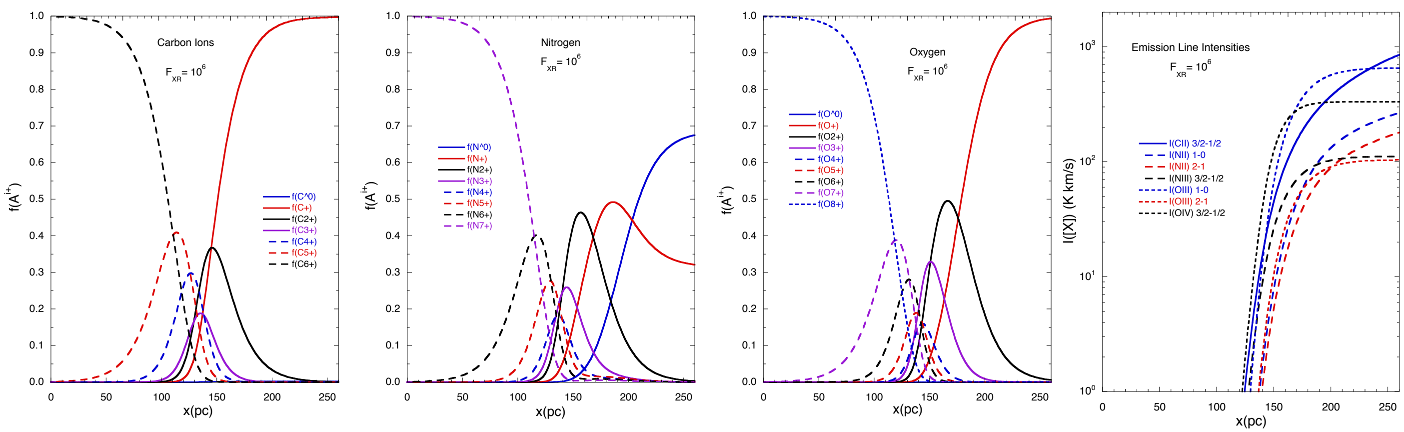
Shown are all the atomic processes determining the ionization balance of oxygen included in the reaction network. Similar reaction networks exist for carbon and nitrogen. The reaction rate coefficients and cross sections for oxygen, carbon and nitrogen, have been assembled and implemented in the X-AGN code.

Results

a) We completed development of a 1-D model of the influence of X-rays in Active Galactic Nuclei (X-AGN) on the distribution of ion states. X-AGN is limited to modeling carbon, nitrogen, and oxygen [8] (see example below [9]).

b) The significance is that we now have a means to study the influence of supermassive black holes on their environment and guide interpretation of current observations and guide observational and instrumental proposals.

c) The next step is to seek external funding to expand and generalized the model to include all the atomic ions that emit diagnostic spectra in galactic nuclei (sulfur, silicon, neon, …) and make it available to the general astronomical community. In the meantime, the current model has supported proposals to ROSES and SOFIA observations, and to support instrument and mission proposals.



Carbon, nitrogen, & oxygen ionization profiles with distance for a 1-D slab located 1 pc from a SMBH [9] with soft X-ray luminosity 10^{44} erg/s. The electron density and temperature of the gas surrounding the SMBH are n(e) = 100/cm^3 and T = 8000K. (far right) The integrated emission intensity profiles, for FIR and MIR fine-structure diagnostic lines. Different emission lines arise at various distances from the SMBH and thus provide diagnostics at various distances in the galactic nucleus.

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