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Infrared Coronal Emission Lines and the Possibility of Their Maser Emission In Seyfert Nuclei

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ABSTRACT

Energetic emitting regions have traditionally been studied via x-ray, UV and optical emission lines of highly ionized intermediate mass elements. Such lines are often referred to as "coronal lines" since the ions, when produced by collisional ionization, reach maximum abundance at electron temperatures of $\sim 10^5 - 10^6$ K typical of the sun's upper atmosphere. However, optical and UV coronal lines are also observed in a wide variety of Galactic and extragalactic sources including the Galactic interstellar medium, nova shells, supernova remnants, galaxies and QSOs.

Infrared forbidden lines typically result from fine structure transitions within the ground electron configuration and are excited predominantly by electron impact. Although these relatively low energy transitions are easily excited, the coronal ionization states are only produced in energetic environments by collisional ionization in a kinetically hot gas or by photoionization in power law continuum radiation fields. In the latter case, coronal emission lines can be produced in relatively low kinetic temperature ($T_e \sim 10^4$ K) or low density ($n_e < 10^5$) plasmas due to their low excitation temperature. As a result of their relatively high critical density ($n_e > 10^6$ cm^{-3}) for collisional de-excitation, coronal fine structure lines are also important coolants of higher density collisionally ionized plasmas. They are produced in a wide variety of environments found in AGN and many Galactic sources

Infrared coronal lines are providing a new window for observation of energetic emitting regions in heavily dust obscured sources such as infrared bright merging galaxies and Seyfert nuclei and new opportunities for model constraints on physical conditions in these sources. Unlike their UV and optical counterparts, infrared coronal lines can be primary coolants of collisionally ionized plasmas with $10^4 < T_e\ (K) < 10^6$ which produce little or no optical or shorter wavelength coronal line emission. In addition, they provide a means to probe heavily dust obscured emitting regions which are often inaccessible to optical or UV line studies. The wide range of critical densities spanned by infrared coronal lines ($5 < \log n_e$ (cm^{-3}) < 10) combined with their reduced extinction make them ideal probes of Seyfert broad line region cloud kinematics. Finally, they are useful for abundance studies in AGN and Galactic sources, and are modeled to be bright in colliding galaxies and galaxy cluster cooling flows.

In this poster, we provide results from new model calculations designed to support upcoming Infrared Space Observatory (ISO) and current ground-based observing programs involving infrared coronal emission lines in AGN. We present a complete list of infrared ($\lambda > 1\ \mu$m) lines due to transitions within the ground configurations $2s^22p^k$ and $3s^23p^k$ ($k = 1$ to 5) or the first excited configurations $2s2p$ and $3s3p$ of highly ionized ($\chi \geq 100$ eV) astrophysically abundant ($n(X)/n(H) \geq 10^{-6}$) elements. Included are approximately 74 lines in ions of O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe, and Ni spanning a wavelength range of approximately $1 - 280\ \mu$m. We present new results from detailed balance calculations, new critical densities for collisional de-excitation, intrinsic photon rates, branching ratios, and excitation temperatures for the majority of the compiled transitions. The temperature and density parameter space for dominant cooling via infrared coronal lines is presented, and the relationship of infrared to optical coronal lines is discussed.

We find that roughly half of the infrared coronal line transitions examined are potentially bright. These relatively bright lines span a wavelength range of $1 < \lambda\ (\mu\text{m}) < 25$ with the majority of the transitions accessible only to space-based and suborbital spectrometers. Several bright transitions can be observed from the ground at sites affording exceptional infrared transmission. For example, recent ground-based observations have revealed that emission lines due to [Si VI] and [Si VII] in NGC 1068 and [Al VI] on NGC 4151 are among the brightest infrared lines in these archetypal galaxies. Critical densities for collisional de-excitation of the brighter transitions span a range of $4.8 \leq \log n_e$ (cm^{-3}) ≤ 9.8 with excitation temperatures spanning

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$3.2 \leq \log(E_j/k)$ (K) ≤ 5.6. The ions themselves reach maximum abundance in collisionally ionized regions at $5.2 \leq logT_e$ (K) ≤ 6.4, but their infrared forbidden lines can also probe cooler (10^4 K) photoionized regions due to their relatively low excitation temperature.

Relatively Bright ($\log[A_{ji}n_j/n_e] \geq -10$) Infrared Coronal Lines of Astrophysically Abundant Elements

Species	Transition	λ (μm)	Species	Transition	λ (μm)
Ar XIII	$^3P_0 - ^3P_1$	c 1.0159(40)	S IX	$^3P_1 - ^3P_0$	c 3.75(3)
S XIII	$^3P_1 - ^3P_2$	c 1.0264(30)	Si IX	$^3P_0 - ^3P_1$	m 3.92(2)
Fe XIII	$^3P_0 - ^3P_1$	m 1.07468(4)	Mg IX	$^3P_1 - ^3P_2$	c 4.06(4)
Fe XIII	$^3P_1 - ^3P_2$	m 1.07979(4)	Ca VII	$^3P_1 - ^3P_2$	c 4.086(5)
S IX	$^3P_2 - ^3P_1$	c 1.2520(20)	Mg IV	$^2P_{1/2} - ^2P_{3/2}$	c 4.487(4)
Ni XIV	$^2D_{3/2} - ^2D_{5/2}$	c 1.28150(12)	Na VII	$^2P_{1/2} - ^2P_{3/2}$	c 4.675(22)
S XI	$^3P_1 - ^3P_2$	c 1.3924(50)	Mg VII	$^3P_1 - ^3P_2$	c 5.50(3)
Si X	$^2P_{1/2} - ^2P_{3/2}$	m 1.4301(4)	Mg V	$^3P_2 - ^3P_1$	m 5.60(2)
S XI	$^3P_0 - ^3P_1$	c 1.9200(70)	Al VIII	$^3P_0 - ^3P_1$	c 5.85(10)
Si XI	$^3P_1 - ^3P_2$	c 1.932(50)	Ar VII	$^3P_1 - ^3P_2$	c 5.95(5)
Si VI	$^2P_{3/2} - ^2P_{1/2}$	m 1.9590(70)	Fe XI	$^3P_1 - ^3P_0$	c 6.082(19)
Al IX	$^2P_{1/2} - ^2P_{3/2}$	m 2.040(7)	Ca VII	$^3P_0 - ^3P_1$	c 6.154(8)
Fe XII	$^2D_{3/2} - ^2D_{5/2}$	c 2.2170(3)†	Na VIII	$^3P_1 - ^3P_2$	c 6.23(3)
Ca XIII	$^3P_1 - ^3P_0$	c 2.258(15)	Si VII	$^3P_1 - ^3P_0$	c 6.515(18)
Ca VIII	$^2P_{1/2} - ^2P_{3/2}$	m 2.32(2)	Ne VI	$^2P_{1/2} - ^2P_{3/2}$	m 7.642(6)
Si VII	$^3P_2 - ^3P_1$	m 2.474(7)	Na VI	$^3P_1 - ^3P_2$	c 8.61(9)
Si IX	$^3P_1 - ^3P_2$	c 2.5839(5)	Mg VII	$^3P_0 - ^3P_1$	c 9.03(9)
Ar XI	$^3P_1 - ^3P_0$	c 2.60(5)	Al VI	$^3P_1 - ^3P_0$	c 9.116(6)
Al X	$^3P_1 - ^3P_2$	c 2.753(20)	Ne VII	$^3P_1 - ^3P_2$	c 10.6(7)
Al V	$^2P_{3/2} - ^2P_{1/2}$	m 2.879(14)	Mg V	$^3P_1 - ^3P_0$	c 13.54(5)
Mg VIII	$^2P_{1/2} - ^2P_{3/2}$	m 3.0275(20)	Na VI	$^3P_0 - ^3P_1$	c 14.3(3)
Ca IX	$^3P_0 - ^3P_1$	c 3.088(13)	Ne V	$^3P_1 - ^3P_2$	m 14.32(3)
Al VI	$^3P_2 - ^3P_1$	m 3.661(14)	Ni XIII	$^3P_1 - ^3P_0$	c 19.3(4)†
Al VIII	$^3P_1 - ^3P_2$	m 3.72(2)	Ne V	$^3P_0 - ^3P_1$	m 24.28(2)
			Ca VI	$^2D_{3/2} - ^2D_{5/2}$	c 24.30(17)

measured or calculated wavelength denoted by *m* and *c* respectively.

We find that under physical conditions found in Seyfert nuclei, 14 of 70 transitions examined have significant population inversions in levels that give rise to infrared coronal lines. Maser gain lengths in these transitions are presented for dense ($10^6 \leq n_e$ (cm^{-3}) $\leq 10^9$) collisionally ionized plasmas. We find that significant maser gains are possible in conditions expected in the intermediate zone of Seyfert nuclei. Application of these results to cooler plasmas photoionized by power law continuum radiation fields is also presented.

Coronal line maser gain lengths for Seyfert nuclei

1	2	3	4	5	6
Species	λ μm	$-log\left[\frac{n(ion)}{n(element)}\right]_{coll}$	$12 + log\left[\frac{n(X)}{n(H)}\right]$	$[l_6]_{coll}$ pc	$[l_9]_{coll}$ pc
Ne V	24.28	0.21	8.09	*a*	$1.7e-3$
Mg V	13.54	0.22	7.58	$1.2e+0$	*a*
Mg VII	9.03	0.30	...	*a*	$3.8e-3$
Al VI	9.12	0.28	6.47	$7.1e+1$	*a*
Al VIII	5.85	0.38	...	*a*	$4.5e-2$
Si VII	6.52	0.30	7.55	$1.9e+1$	$1.6e-2$
S IX	3.75	0.35	7.21	$3.4e+2$	$1.9e-3$
S X	8.68	0.35	....	$9.8e+2$	$5.6e-3$
Ar XI	2.60	0.39	6.56	$7.7e+3$	$1.3e-2$
Ca VII	6.15	0.35	6.36	*a*	$1.0e-3$
Ca XIII	2.26	0.41	...	$3.3e+4$	$4.2e-2$
Ca XIV	1.31	0.41	...	$1.3e+6$	$1.3e+0$
Fe XI	6.08	0.57	7.67	*a*	$3.3e-3$
Fe XII	2.22†	0.53	...	$7.9e+2$	$3.9e-3$

5, 6 – column length for maser gain of e^1 evaluated at $n_e = 10^6$ and 10^9 cm^{-3}
a – no inversion at this density