9-1-1993

A Masing [Fe XI] Line

Gary J. Ferland
University of Kentucky, gary@uky.edu

Repository Citation

Ferland, Gary J., "A Masing [Fe XI] Line" (1993). *Physics and Astronomy Faculty Publications*. 167.
https://uknowledge.uky.edu/physastron_facpub/167

A Masing [Fe XI] Line

Notes/Citation Information
Published in *The Astrophysical Journal Supplement Series*, v. 88, no. 1, p. 49-52.

Digital Object Identifier (DOI)
http://dx.doi.org/10.1086/191814

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 88:49–52, 1993 September

A MASING [Fe XI] LINE

G. J. FERLAND[1]
Department of Physics and Astronomy, The University of Kentucky, Lexington, KY 40506
Received 1992 June 25; accepted 1993 January 22

ABSTRACT

I draw attention to a maser which occurs within the ground term of Fe^{+10}. In many photoionized environments, infrared fine-structure lines and the [O I] λ6300 line become optically thick but maser amplification of ionic fine-structure lines is unusual. During the course of development of a code designed to simulate gas under radiative-collisional equilibrium, the radiative transfer of roughly 500 ionic/atomic emission lines has been treated using escape probabilities. Nearly all forbidden lines can become optically thick under extreme conditions, but the $^3Pj = 1, 0$ [Fe XI] 6.08 μm transition is the only line which routinely mases and can reach optical depths smaller than −5. Maser effects can alter the intensity ratio of the infrared line relative to $^3Pj = 2, 1$ λ7892 by half an order of magnitude under certain conditions. A model of the coronal line region of Nova Cyg 1975 is presented, which illustrates the effects of this maser.

Subject headings: atomic processes — galaxies: active — galaxies: Seyfert — infrared: galaxies — masers

1. INTRODUCTION

Maser amplification is frequently encountered in molecular phases of the interstellar medium at radio energies, but it is not a common property of hot ionized gases, the subject of this paper. It has long been known that infrared fine-structure lines can become optically thick in ionized regions, especially under high-luminosity conditions (Rubin 1983). This is surprising at first thought, since the lines are strongly forbidden, but their low transition probability is more than made up for by the large phase-space factor multiplying the transition probability to convert it into an absorption cross section. Although these transitions routinely become optically thick, they generally do not mase.

Peculiarities in the ratios of collision to radiative transition probabilities can, for some transitions, cause the line source function

$$S_{u,l} \equiv \frac{n_u/g_u}{n_l/g_l - n_u/g_u} \qquad (1)$$

to become negative (see, for example, Elitzur 1992). Here n_i is the density of atoms in level i (cm^{-3}), g_i is the statistical weight of the level, and u and l represent the upper and lower levels. A population inversion (negative line source function) occurs if the ratio of the populations per sublevel

$$r \equiv \frac{(n_u/g_u)}{(n_l/g_l)} \qquad (2)$$

grows larger than unity. When $r > 1$, negative line optical depths and maser emission (enhanced by the escape probability $[1 - \exp(-\tau)]/\tau$) occur. Although maser emission is frequently encountered in cool molecular regions (Elitzur 1992), it is very rare to find strong masers in optical or near-IR line emission (see, however, Greenhouse et al. 1993, who also discuss this issue).

2. THE CASE OF [Fe XI]

A very strong maser has been encountered within the ground term of the Fe^{+10} ion. Several "coronal" lines were incorporated into the radiative-collisional equilibrium code Cloudy (Ferland 1993; this work was described by Korista & Ferland 1989). Line optical depths for all IR lines are treated using the full line optical depth, which is proportional to $n_l/g_l - n_u/g_u$. Negative optical depths and maser emission occur if the ratio r exceeds unity and this difference becomes negative.

Figure 1 shows a partial Grotrian diagram for the ^3P ground term of Fe^{+10} (Sugar & Corliss 1985). The lower $j = 1, 2$ λ7892 transition has, for instance, been observed in several Seyfert galaxies (Grandi 1978). A second transition, the $j = 0, 1$ 6.08 μm IR line, is the subject of this article. Routine testing of the code has disclosed that strong maser emission, with optical depths sometimes smaller than −20, is frequently encountered in the 6.08 μm line.

The basic reason that the IR transition is so strongly masing has to do with the ratio of collisional to radiative transition rates. Consider the population of the excited $j = 0$ and $j = 1$ levels in the low-density limit. In this case the population of either excited level is determined by the balance between collisional excitation from the ground level and radiative deexcitation from the excited level. Then the population of the excited level is $n_u = n_l q_{l,u} n_e / A_{u,l}$ where the q's and As are the collisional excitation rate coefficients and spontaneous transition probabilities, and for the moment I neglect radiative transfer effects.

---

[1] Visiting Astronomer, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories, Inc., which is operated uner cooperative agreement with the National Science Foundation.

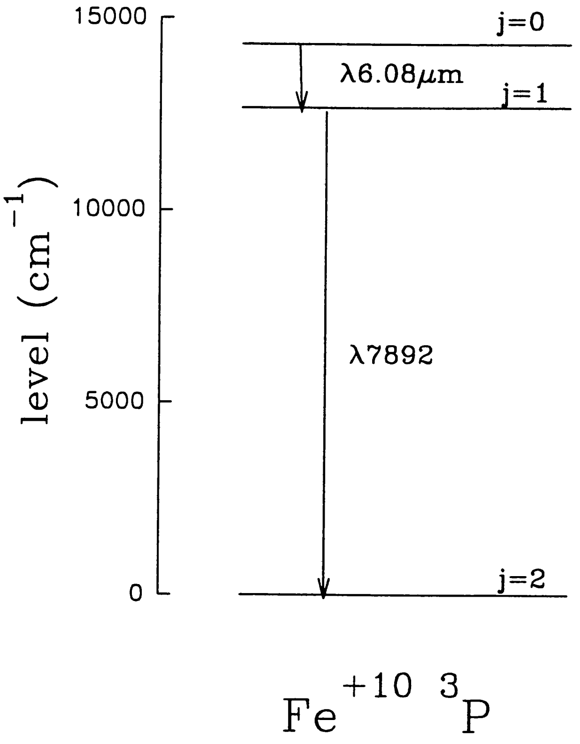

FIG. 1.—Grotrian diagram for the ^3P ground term of Fe^{+10}. The energy levels are drawn to scale and are unusual since the energy splitting is nearly in a 10:1 ratio rather than the more typical 1:1 ratio. As a result the transition probability for the $j = 0, 1$ transition is several orders of magnitude smaller than that for the $j = 1, 2$ transition, and the ratio of the populations of the $j = 0$ to $j = 1$ levels is well above the infinite thermal limit.

Then, in this low-density limit, the ratio r (eq. [2]) is given by

$$r = \frac{n_0/g_0}{n_1/g_1} \approx \frac{\Omega_{2,0}/g_0}{\Omega_{2,1}/g_1}\frac{A_{2,1}}{A_{2,0}} \exp(-2365/T_e)$$
$$= \frac{0.11}{0.09}\frac{43.6}{0.23} \exp(-2365/T_e) \sim 180 , \qquad (3)$$

where the subscripts denote the j quantum numbers.

The transition probabilities used in equation (3) were taken from the calculations of Mendoza & Zeippen (1983). Distorted wave collision strengths from Mason (1975) are adopted, since no more recent calculations have been performed. Adopting these numbers, we find the indicated ratio of ~200 at a temperature of 10^4 K. The level populations are strongly inverted ($r \gg 1$), and maser emission will occur if the $j = 0, 1$ transition is optically thick.

A series of calculations have been performed in which the populations of the $j = 2$, 1, and 0 levels of the ground term are determined by solving the full set of statistical equilibrium equations including collision and radiative transitions within the three levels of the ground term. The calculations assume an electron temperature of 10^4 K and neglect higher levels. Treating only three levels is warranted in the present study since this temperature is low enough for excitation to the next level (at 4.7 eV) to be negligible. Excitation to or from higher levels can have a significant effect on the population of low-lying levels when temperatures are high, as in the case of the solar corona (see, for example, Mason 1975). The source function ratio (eq. [1]) for the masing $j = 0, 1$ transition was then determined, and the results of these calculations are shown in Figure 2. A negative line source function is found for all densities low enough for the term to be out of thermal equilibrium ($n \ll 10^{10}$ cm^{-3}). For densities substantially in excess of 10^{10} cm^{-3}, collisions bring the levels into thermodynamic equilibrium, and the level populations go to the thermal limit. The source function is, of course, positive in this limit.

In the previous discussion the reason the IR line mases was posed in terms of the ratio of transition probability to collision rate. The collision rates for excitation of the two transitions are similar, so the real reason the line suffers an inversion is that the transition probability for the 0, 1 transition is so much smaller than for the 1, 2 transition. This is basically due to the small energy of the 0, 1 transition relative to the 1, 2 transition. The line oscillator strength is related to the transition probability and wavelength by

$$g_u f_{\rm em} = 1.499 \times 10^{-8} A_{u,l} \lambda^2_{\mu{\rm m}} . \qquad (4)$$

where the wavelength is in microns and we see the result that, for a given oscillator strength, an infrared line will have the smaller transition probability (see, for example, Mihalas 1978). This is despite the fact that these lines tend to have the larger line center opacity; the absorption cross section and oscillator strength are related by

$$a_{\rm crs} = 0.0150 f \lambda . \qquad (5)$$

The line mases because, although the collision rates are simi-

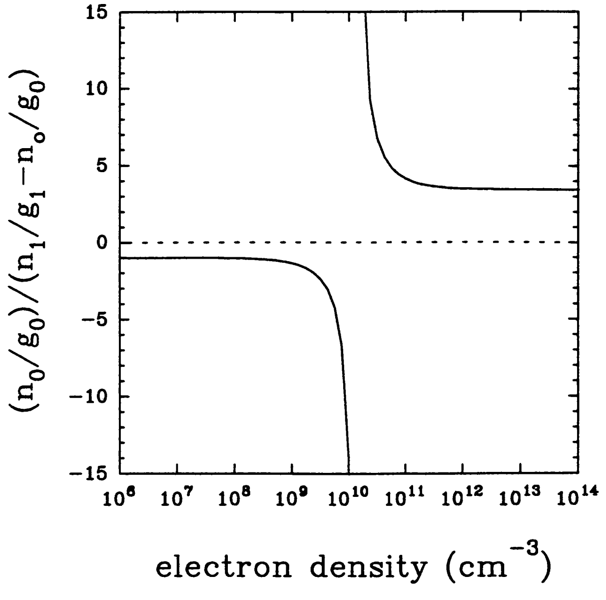

FIG. 2.—Source function for the $j = 0, 1$ transition. In the low-density limit, ($n_e \ll 10^{10}$ cm^{-3}) is close to the fully saturated maser limit of −1. Well above 10^{10} cm^{-3}, the levels are controlled by collisions and the thermodynamic equilibrium limit is reached. Negative optical depths and maser emission are common occurrences when the density is less than 10^{10} cm^{-3}.

lar, the radiative rates differ by a great deal since the energy splitting between the levels within the term are so different. This is very unusual for lines within the ^3P ground term; they normally have a more nearly 1:1 ratio of energies. Tracing all the physics back to its source, the reason the 0, 1 line mases is that the energy splitting between the 0 and 1 levels is nearly 10 times smaller than that between the 1 and 2 levels, so that the transition with the smaller energy have the longer lifetime, and a greater opportunity to become overpopulated. Thus the peculiarity of the [Fe XI] maser can be traced to peculiarities in the atom's structure.

A simple estimate relates the path needed for the [Fe XI] line to mase, to the iron abundance and density. Limiting our discussion to densities well below 10^{10} cm^{-3}, the thermal limit for the levels under consideration, we find a level population of j = 1 level which is simply related to the excitation rate by

$$\begin{aligned} n_1 &\approx n(\mathrm{Fe}^{+10})\frac{q_{2,1}n_e}{A_{2,1}} \\ &\approx n_e n(\mathrm{Fe}^{+11})1.07\times10^{-10}\exp(-1.82/t_4)t_4^{-1/2}, \quad (6) \end{aligned}$$

where t_4 is the temperature in units of 10^4 K. Then neglecting stimulted emission the optical depth is given by

$$\tau \approx 2\times10^{-28}n_e n(\mathrm{Fe}^{+11})t_4^{-1}\exp(-1.82/t_4)L, \quad (7)$$

where L is the path. If iron has a solar abundance (Grevesse & Anders 1989) and all iron is in the form of Fe^{+10}, then

$$\tau \approx 1\times10^{-32}n_p^2 t_4^{-1}\exp(-1.82/t_4)L. \quad (8)$$

The line will mase if the density is well below 10^{10} cm^{-3} and the transition optically thick. This estimate will be used in the following section.

3. AN APPLICATION TO NOVAE

The estimates made above show that the j = 0–1 transition within the Fe^{+10} ground term will have an inverted level population when the densities are low enough for the populations to be out of thermodynamic equilibrium. Here I present a series of numerical simulations of photoionized regions where the maser effects described above are especially important.

Coronal lines (the [Fe XI] λ7894 line is one) are strong in certain stages of the outburst of classical novae (Grasdalen & Joyce 1976, 1980; Greenhouse et al. 1989; Ferland, Lambert, & Woodman 1977, 1986). This region could be shock heated (Ferland et al. 1986) or more likely photoionized by the radiation field of the remnant, now known to have temperatures well in excess of 10^5 K (Williams et al. 1991; Ögelman, Krautter, & Beuermann 1987). The calculations presented below are meant to stimulate the regions emitting the coronal lines observed in novae, if these regions are indeed under conditions of photoionization equilibrium.

A simple estimate shows that the infrared [Fe XI] coronal line can readily mase in novae. Estimates show that the density in the coronal line region of V1500 Cygni (Nova Cygni 1975) may be on the order of 10^9 cm^{-3} (although this value is highly uncertain; see Ferland et al. 1977, 1986). The abundance of iron in ejecta of V1500 Cyg was basically solar (Ferland & Shields 1978). Then, applying the previous equation, we see that a path of 10^{14} cm is needed for the iron maser to reach an optical depth of −1 for this density. This is easily within the scope of the ejecta, with the result that line maser emission can readily occur. I now go on to perform numerical simulations which confirm this estimate.

The radiative equilibrium code most recently described by Ferland (1993) is used. For simplicity, solar abundances are assumed (Grevesse & Anders 1989) and the ionizing radiation field is taken to be a blackbody with a temperature of 2×10^5 K. It is likely that second row heavy elements are enhanced in most novae (Starrfield 1992) but the abundance of iron, and several other third row elements, was basically solar in Nova Cyg 1975 (Ferland & Shields 1978). These studies were of the nebular phase in the ejecta, not the coronal line region. It is not known whether the two regions have similar metallicities (ablation from the secondary, for instance, could alter the abundances of certain regions). Solar abundances are the simplest and are the best treatment for the present purposes, since iron is likely to have a solar abundance. An isochoric hydrogen density of 10^9 cm^{-3} is assumed; this was chosen to be below the critical density for the levels to thermalize. Actually there are

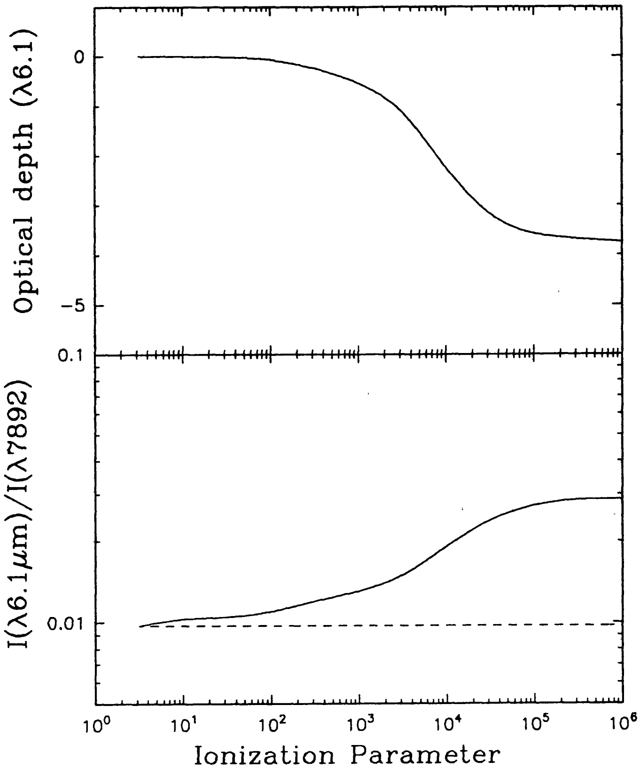

FIG. 3.—The [Fe XI] fine-structure lines for the coronal line region of Nova Cyg 1975. The ionization parameter is indicated along the x-axis. The upper panel shows the optical depth in the j = 0, 1 transition. The lower panel shows the predicted intensity ratio of the j = 0, 1 to j = 1, 2 transition, with maser effects included (*solid line*) and with line optical depths disabled (*dotted curve*). The line amplification due to negative optical depths increases the line intensity ratio by half an order of magnitude.

few indications of the density of the coronal line region in novae, but this estimate is reasonable (Saizar et al. 1992).

Figure 3 shows the results of these simulations. The calculations are parameterized by an ionization parameter U, defined as the dimensionless ratio of the ionizing photon to total hydrogen (in all forms) density. This ionization parameter is the X-axis on the figure. The calculations stopped at the He^{++}–He^{+} ionization front, a point where very little Fe^{+10} was present. The upper panel of the figure shows the optical depth in the $j = 0$, 1 transition, and the lower panel shows the ratio of the intensities of the $j = 0$, 1 to 1, 2 transitions, both for the complete simulation, and for a trial case in which line optical depths were set to zero. For large ionization parameters the 0, 1 transition becomes quite optically thick, and the intensity ratio increases as the result of maser amplification. The intensity ratio has only a very weak temperature dependence (eq. [3]) so, were maser effects not present, the line ratio would have remained constant. This is confirmed by the second line in the lower panel, which shows the intensity with the optical depth set to zero.

4. DISCUSSION

The discussion above has shown that the [Fe XI] 6.08 μm line will usually have a negative opacity at low ($n \ll 10^{10}$ cm^{-3}) densities, and that under some circumstances significant line optical depths and maser amplification will result. This is the only one of the approximately 500 ionic lines now incorporated in Cloudy which has undergone strong maser effects during routine testing of the code. Although masers are common in molecules at radio wavelengths (Elitzur 1992), they apparently are seldom encountered in ions.

The previous section showed that it is possible that the [Fe XI] line in a coronal line region like that present in Nova Cyg 1975 could undergo maser emission. This is interesting purely from both phenomenological and atomic physics points of view; few ion masers are encountered in nature. The detection of the both lines within the Fe^{+10} ground term could also prove a great deal of information concerning the physical conditions in the coronal line region. This, together with other lines, could be used to indicate temperature, density, and iron abundances in this region.

The [Fe XI] maser could have other applications. For instance, it could serve as a probe of the infrared radiation field produced in active nuclei if substantial negative optical depths do occur. The [Fe XI] λ7892 transition has long been observed in Seyfert galaxies (Grandi 1978). The 6.1 μm line has not been detected so far to the best of my knowledge, but if the conditions within the coronal line region of AGNs are such that the line mases, then it will be quite sensitive to the infrared background continuum which could pump it. In this case the 6.08 μm/λ7892 intensity ratio could serve as a diagnostic indicator of the IR continuum actually striking emission-line gas, as opposed to that we observe (see the discussion on maser illumination in Elitzur 1992). Such observations could then test theories of the unification of the various classes of AGNs, which do predict decidedly nonisotropic continuum emission.

This work was supported by the National Science Foundation through grant AST 90-19692. I wish to thank the referee, Hagai Netzer, for his comments, which clarified the presentation in this paper.

REFERENCES

Elitzur, M. 1992, Astronomical Masers (Dordrecht: Kluwer)
Ferland, G. J. 1993, University of Kentucky Physics and Astronomy Department Internal Report: Hazy, a Brief Introduction to Cloudy
Ferland, G. J., Lambert, D. L., & Woodman, J. 1977, ApJ, 213, 132
———. 1986, ApJS, 60, 375
Ferland, G. J., & Shields, G. A. 1978, ApJ, 226, 172
Grandi, S. A. 1978, ApJ, 221, 501
Grasdalen, G., & Joyce, R. R. 1976, Nature, 259, 187
———. 1980, unpublished
Greenhouse, M. A., et al. 1993, ApJS, 88, 23
Greenhouse, M. A., Grasdalen, G. L., Hayward, T. L., Gehrz, R. D., & Jones, T. J. 1989, AJ, 95, 172
Grevesse, N., & Anders, E. 1989, in Cosmic Abundances of Matter, ed. C. J. Waddington (New York: AIP), 1
Korista, K. T., & Ferland, G. J. 1989, ApJ, 343, 678
Mason, H. E. 1975, MNRAS, 170, 651
Mathews, W. G., & Ferland, G. J. 1987, ApJ, 323, 456
Mendoza, C., & Zeippen, C. J. 1983, MNRAS, 202, 981
Mihalas, D. 1978, Stellar Atmospheres (2d ed.; San Francisco: W. H. Freeman)
Ögelman, H., Krautter, J., & Beuermann, K. 1987, A&A, 177, 110
Rubin, R. H. 1983, ApJ, 274, 671
Saizar, P., et al. 1992, ApJ, 400, 651
Starrfield, S. 1992, in Binary Stars, ed. J. Sahade & Y. Kondo (Dordrecht: Kluwer), 376
Sugar, J., & Corliss, C. 1985, J. Phys. Chem. Ref. Data, 14, Suppl 2.
Williams, R. E., Hamuy, M., Phillips, M. M., Heathcotte, S. R., Wells, L., & Navarrete, M. 1991, ApJ, 376, 721