FIRST APPLICATION OF THE Fe XVII I(17.10 Å)/I(17.05 Å) LINE RATIO TO CONSTRAIN THE PLASMA DENSITY OF A COSMIC X-RAY SOURCE

CHRISTOPHER W. MAUCHE, DUANE A. LIEDAHL, AND KEVIN B. FOURNIER
Lawrence Livermore National Laboratory, L-43, 7000 East Avenue, Livermore, CA 94550;
mauche@lbnl.gov, fournier2@llnl.gov

Received 2001 April 30; accepted 2001 June 27

ABSTRACT

We show that the Fe XVII I(17.10 Å)/I(17.05 Å) line ratio observed in the Chandra High-Energy Transmission Grating (HETG) spectrum of the intermediate polar EX Hya is significantly smaller than that observed in the Sun or other late-type stars. Using the Livermore X-Ray Spectral Synthesizer, which calculates spectral models of highly charged ions based on HULLAC atomic data, we find that the observed I(17.10 Å)/I(17.05 Å) line ratio can be explained if the plasma density $n_e \gtrsim 3 \times 10^{14}$ cm$^{-3}$. However, if photoexcitation is included in the level-population kinetics, the line ratio can be explained for any density if the photoexcitation temperature $T_{bb} \gtrsim 55$ K. For photoexcitation to dominate the Fe XVII level-population kinetics, the relative size of the hot spot on the white dwarf surface must be $f \lesssim 2\%$. This constraint, and the observed X-ray flux, requires a density $n \gtrsim 2 \times 10^{14}$ cm$^{-3}$ for the post-shock flow. Either way, then, the Chandra HETG spectrum of EX Hya requires a plasma density that is orders of magnitude greater than that observed in the Sun or other late-type stars.

Subject headings: atomic processes È binaries: close È stars: individual (EX Hydrae) È plasma fields: Sun: corona È X-rays: binaries

1. INTRODUCTION

Because of the high abundance of Fe, the persistence of Ne-like Fe over a broad temperature range ($T \approx 2$–12 MK), and the large collision strengths for $2p \rightarrow nd$ transitions, the $2p^6-2p^53l$ ($l = s, d$) lines of Fe XVII at 15–17 Å are prominent in the X-ray spectra of high-temperature plasmas found in settings as diverse as tokamaks (Klapisch et al. 1978; Phillips et al. 1997; Beiersdorfer et al. 2001), the Sun (Rugge & McKenzie 1985; Phillips et al. 1997; Saba et al. 1999), and both late- and early-type stars (Canizares et al. 2000; Ayres et al. 2001; Kahn et al. 2001; Waldron & Cassinelli 2001). The importance of Fe XVII has engendered numerous studies of its atomic structure and level-population kinetics, usually with an emphasis on the temperature dependence of line ratios within the 2p–3s and 2p–3d multiplets (Rugge & McKenzie 1985; Smith et al. 1985; Raymond & Smith 1986). In this paper, we focus on the density dependence of the Fe XVII X-ray spectrum.

The lowest lying configurations of Fe XVII are the $2p^6$ ground state, the $2p^53s$ multiplet (4 levels, $E = 725.3–739.0$ eV), the $2p^53p$ multiplet (10 levels, $E = 754.3–789.6$ eV), and the $2p^53d$ multiplet (12 levels, $E = 800.3–826.0$ eV). Because electron impact excitation from the ground state is strong for transitions into the $2p^5nd$ configurations, but weak for transitions into the $2p^53s$ configuration, the population flux into the lowest lying configuration is dominated by radiative cascades originating on higher lying energy levels, rather than direct excitation from the ground state (Loulgergue & Nussbaumer 1973). The four levels of the $2p^53s$ configuration have, in increasing energy order, total angular momenta $J = 2, 1, 0,$ and $1$. The $2p^5-2p^53s(J = 0)$ transition is strictly forbidden, but the remaining three levels, $J = 2, 1,$ and $1$, decay to ground, producing lines at 17.10, 17.05, and 16.78 Å, respectively. The 17.10 Å line is produced by a magnetic quadrupole transition, but it is nevertheless bright, because the upper level is populated efficiently by radiative cascades, and its radiative branching ratio to ground is 1.0. Since the radiative decay rate of this transition is slow compared to the other 2p–3l lines, collisional depopulation sets in at lower densities. Thus, the intensity ratio of the 17.10 Å line to any of the other 2p–3l lines provides a diagnostic of the plasma density, as was first pointed out by Klapisch et al. (1978).

Of these density-dependent line ratios, we study primarily the $I(17.10 \text{ Å})/I(17.05 \text{ Å})$ line ratio, which has a critical density of a few $\times 10^{14}$ cm$^{-3}$. To utilize this diagnostic in a cosmic X-ray source, we require an instrument with sufficient spectral resolution to cleanly resolve the two lines and a bright X-ray source with high characteristic densities, intrinsically narrow lines, and low interstellar absorption. The instrumental requirements are supplied by the High-Energy Transmission Grating Spectrometer (Markert et al. 1994) aboard the Chandra X-Ray Observatory, and the source requirements are satisfied by nearby magnetic cataclysmic variables (CVs): semidetached binaries composed of a magnetic ($B \sim 1$–100 MG) white dwarf primary and a low-mass secondary. The global properties are different for polars (AM Her stars) and intermediate polars (DQ Her stars), but in both classes of magnetic CVs, the flow of material lost by the secondary is channeled onto small spots on the white dwarf surface in the vicinity of the magnetic poles. Before reaching the stellar surface, the supersonic $[v_\text{eff} = (2GM_{\text{wd}}/R_{\text{wd}})^{1/2} \approx 3600 \text{ km s}^{-1}]$ flow passes through a strong shock ($T_s = 3GM_{\text{wd}}\mu_{\text{wd}}/8R_{\text{wd}} \approx 200$ MK), where most of its kinetic energy is converted into thermal energy. For a mass-accretion rate $M = 10^{15} \text{ g s}^{-1}$ ($L_x = GM_{\text{wd}}/2R_{\text{wd}} \approx 3 \times 10^{31} \text{ ergs s}^{-1}$) and a relative spot size $f = 0.1$, the density of the flow immediately behind the shock is $n = M/4\pi R_{\text{wd}}^2\mu_{\text{wd}}(v_\text{eff}/4) \approx 10^{13}$ cm$^{-3}$. As the flow settles onto the white dwarf, it cools and its density increases, so the density is significantly higher where the temperature reaches a few million degrees, where Fe XVII is the dominant charge state of Fe. Doppler broadening of the emission lines is reduced because of the ordered,
quasi-radial geometry and the ever-decreasing velocity ($v < v_{th} / 4 \approx 900 \text{ km s}^{-1}$, hence $\Delta \lambda / \lambda < 3 \times 10^{-3}$) of the postshock flow.

With its bright X-ray emission lines and low interstellar absorption, the well-studied (Hellier et al. 1987; Rosen, Mason, & Cordova 1988; Hurwitz et al. 1997; Fujimoto & Ishida 1997; Allan, Hellier, & Beardmore 1998; Mauche 1999) intermediate polar EX Hya is an ideal magnetic CV in which to study high-density plasmas. Spectroscopic evidence for high densities in this source is provided by Hurwitz et al. (1997), who used the ratio of the Fe xx/Fe xxiii 133 Â blend to the Fe xxiii 129 Â line observed in an Extreme Ultraviolet Explorer short-wavelength spectrum to infer a density $n_e \gtrsim 10^{13}$ cm$^{-3}$ for the $T_e \sim 10$ MK plasma in EX Hya. Below, we use the Fe xvii $I(17.10)$/$I(17.05)$ Â line ratio observed in a Chandra High-Energy Transmission Grating (HETG) spectrum to infer a density $n_e \gtrsim 3 \times 10^{14}$ cm$^{-3}$ for the $T_e \sim 4$ MK plasma in EX Hya. We discuss the observations and analysis in § 2 and Fe xvii spectral models in § 3, and close with a summary and discussion in § 4.

2. OBSERVATIONS AND ANALYSIS

The Chandra HETG/ACIS-S observation of EX Hya was performed between 2000 May 18 9$^h$41$^m$ and May 19 20$^h$54$^m$ UT for a total exposure of 59.1 ks. Extraction of the grating spectra and calculation of the effective area files was accomplished with the CIAO 2.1 suite of software using the reprocessed data products and new calibration data files (version R4CU5UPD8) for sequence 300041. A preliminary discussion of the resulting medium-energy grating (MEG) and high-energy grating spectra has been presented by Mauche et al. (2000) and Mauche (2000); here we discuss only the MEG spectrum as it bears on the Fe xvii emission spectrum.

A detail of the MEG spectrum from 14.5 to 17.5 Â is shown in Figure 1. This representation of the spectrum, in counts s$^{-1}$ Â$^{-1}$, combines $\pm$ first orders and is binned by a factor of 2 to $\Delta \lambda = 0.01$ Â. As indicated along the top of the figure, the spectrum contains emission lines of Fe xvii, Fe xviii, and O viii. The striking aspect of this spectrum is the absence of the Fe xvii 17.10 Â emission line, a feature seen in X-ray spectra of the Sun (Rugge & McKenzie 1985; Phillips et al. 1997; Saba et al. 1999) and other late-type stars (Canizares et al. 2000; Ayres et al. 2001).

To determine the flux in the Fe xvii emission lines, we fit the MEG spectrum over the 14.72–15.55 Â plus 16.68–17.20 Â wavelength interval with a model consisting of a linear background (to account for the thermal bremsstrahlung continuum obvious in the broadband spectrum) and eight Gaussians (to account for the six Fe xvii lines and two intervening O viii Lyman lines). Assuming a common Gaussian width and offset, the fitting function $I(\lambda; \omega) = a_1 + a_2(\lambda - \lambda_0) + \sum_i 12 \omega_i \exp \left[-(\lambda - \lambda_i - a_3)^2/2a_4^2\right]$. Fitting the MEG spectrum in $\Delta \lambda = 0.005$ Â bins, separately accounting for $\pm$ first orders, results in 540 data points and 528 degrees of freedom. For the wavelengths $\lambda_i$, we assume the values measured by Brown et al. (1998) for Fe xvii and tabulated by Kelly (1987) for O viii. The resulting fit, combining $\pm$ first orders, is shown in the thick gray curve in Figure 1. It gives $\chi^2/(\text{degrees of freedom}) = 358/528 = 0.7$, and fit parameters as follows: wavelength offset $a_3 = 4.4 \pm 0.1$ mÅ, Gaussian width $a_4 = 0.74 \pm 0.14$ mÅ, and line fluxes $I(15.01)$ = (3.1 $\pm$ 0.2) $\times$ 10$^{-4}$, $I(15.26)$ = (1.3 $\pm$ 0.2) $\times$ 10$^{-4}$, $I(15.45)$ = (1.3 $\pm$ 1.5) $\times$ 10$^{-3}$, $I(16.78)$ = (2.5 $\pm$ 0.2) $\times$ 10$^{-4}$, $I(17.05)$ = (4.2 $\pm$ 0.3) $\times$ 10$^{-4}$, and $I(17.10)$ = (2.0 $\pm$ 1.6) $\times$ 10$^{-5}$ photons cm$^{-2}$ s$^{-1}$. The wavelength offsets and line widths are consistent with zero, given the absolute wavelength accuracy ($\pm$11 mÅ) and spectral resolution ($\Delta \lambda = 23$ mÅ) of the MEG.

With six line fluxes, we can form five independent line ratios, and to compare our values with those measured in the Sun, we follow Phillips et al. (1997) and Saba et al. (1999), and use the 16.78 Â line as the reference; other line ratios of interest are $I(15.26)$/$I(15.01)$ and $I(17.10)$/$I(17.05)$ Â. These photon-flux line ratios are listed in the middle column of Table 1. It is important to note that these ratios are virtually unaffected by interstellar absorption:

| TABLE 1 |
| Fe xvii Line Ratios |
| --- |
| EX Hya |
| Sun |
| $I(15.01)$/$I(16.78)$,...... | 1.23 $\pm$ 0.15 | 1.04 $\pm$ 0.13 |
| $I(15.26)$/$I(16.78)$,...... | 0.50 $\pm$ 0.09 | 0.51 $\pm$ 0.08 |
| $I(15.45)$/$I(16.78)$,...... | 0.05 $\pm$ 0.06 | ...... |
| $I(17.05)$/$I(16.78)$,...... | 1.65 $\pm$ 0.20 | 1.40 $\pm$ 0.20 |
| $I(17.10)$/$I(16.78)$,...... | 0.08 $\pm$ 0.07 | 1.32 $\pm$ 0.14 |
| $I(15.26)$/$I(15.01)$,...... | 2.46 $\pm$ 0.42 | 2.02 $\pm$ 0.28 |
| $I(17.10)$/$I(17.05)$,...... | 0.05 $\pm$ 0.04 | 0.93 $\pm$ 0.11 |
Far smaller in EX Hya.

I

equivalently, the other, with the exception of the middle panel of Figure 2. We see that the line ratios measured in EX Hya and the Sun are plotted in the right column of Table 1 (weighted mean and standard deviation). The Fe line ratio can be in the "high-density limit" (f/i \approx 0) regardless of the density. Photoexcitation has been shown to explain the low f/i line ratios of early-type stars (Kahn et al. 2001; Waldron & Cassinelli 2001), and could explain the low f/i and Fe xvii I(17.10 Å)/I(17.05 Å) line ratios observed in EX Hya.

To account for photoexcitation, we included in the LXSS population-kinetics calculation the photoexcitation rates \( n e^2/m_e c f_{ji} F_j(T) \), where \( F_j(T) \) is the continuum spectral energy distribution, and \( f_{ji} \) are the oscillator strengths of the various transitions. For simplicity, we assume that \( F_j(T) = (4\pi/h\nu)_B(T_{bb}) \) (i.e., the radiation field is that of a blackbody of temperature \( T_{bb} \)) and that the dilution factor of the radiation field is equal to \( \frac{f}{i} \) (i.e., the X-ray-emitting plasma is in close proximity to the source of the photoexcitation continuum). Both of these assumptions tend to overestimate the importance of photoexcitation. First, the actual intrinsic spectrum of EX Hya probably has a strong break at the Lyman limit, whereas a blackbody does not. This difference affects transitions with energy spacings \( \Delta E > 13.6 \text{ eV} \), such as the 1s2s \({}^3S_i\)-1s2p \(^3P_{2,1}\) (\( f \rightarrow i \)) transitions in Si and S, but not those of O, Ne, and Mg. Second, the UV-EUV continuum in EX Hya must be due to both the accretion disk and the accretion-heated surface of the white dwarf. By assuming that the dilution factor is equal to \( \frac{f}{i} \), we are in effect assuming that the accretion-heated surface of the white dwarf is the dominant source of the UV-UV light. This assumption is justified on the basis of the similarity of the shape and intensity of the far ultraviolet (FUV) spectrum of EX Hya (with a disk) and AM Her (without a disk; Mauche 1999). With these assumptions, we find for a black-body temperature \( T_{bb} = 30 \text{ K} \) (see below) that all the He-like f/i line ratios through Si xiii are significantly affected by photoexcitation, whereas the Fe xvii I(17.10 Å)/I(17.05 Å) line ratio is not.

To understand this result, we show in Figure 3 a schematic of the important level-population processes for the 2p\(^3\)s(J = 2) level of Fe xvii: the 17.10 Å radiative decay (downward-pointing wavy line), collisional excitations (upward-pointing straight lines), and photoexcitations (upward-pointing wavy lines). Since the 2p\(^3\)s(J = 2) level is the first excited level in Fe xvii, we denote it by the sub-
Fig. 3.—Level-population processes in Ne-like Fe XVII. We show the 2p⁶–2p³s radiative decays (downward-pointing wavy lines) and the dominant collisional excitation (upward-pointing straight lines) and photoexcitation paths (upward-pointing wavy lines) out of the 2p³s(J = 2) level. Numbers associated with the lines are, respectively, the radiative decay rate \( A_j \), collision rate coefficients \( \gamma_{J,j} \) for \( T_e = 4 \) MK, and oscillator strengths \( f_j \).

The numbers associated with the lines are respectively the radiative decay rate \( A_j \), the collision rate coefficients \( \gamma_{J,j} \) for \( T_e = 4 \) MK, and the oscillator strengths \( f_j \).

R(15.45 Å) line ratio shows the least. The theoretical ratios are compared with the observed ratios for EX Hya and the Sun in the middle panel of Figure 2. As with other theoretical models of Fe XVII (Brown, Beiersdorfer, & Widmann 2001), we are unable to reproduce the observed R(15.01 Å) [hence the \( I(15.01 \text{ Å})/I(15.26 \text{ Å}) \)] line ratio, although the value we measure for this ratio is consistent with that measured in the Sun. The observed R(15.26 Å) and R(15.45 Å) line ratios are as predicted by our models, but the R(17.05 Å) and R(17.10 Å) line ratios are too high and too low, respectively, unless the plasma density \( n_e \geq 3 \times 10^{14} \text{ cm}^{-3} \).

It is alternatively possible that the observed R(17.10 Å) line ratio could be explained if the effective temperature of the photoexcitation continuum is greater than assumed for the set of models discussed above. Indeed, following Gänsicke, Beuermann, & de Martino (1995), Mauche (1999) proposed that the spin-phase modulation of the FUV flux of EX Hya is the result of the varying aspect of a \( T_{bb} \approx 37 \) kK hot spot on a \( T_{bb} \approx 20 \) kK white dwarf. To investigate the consequences of a hotter photoexcitation continuum, we assumed for our second set of models that \( T_e = 4 \) MK (the peak of the Fe XVII ionization fraction) and \( T_{bb} = 30, 40, 50, 60 \) kK. The results of these calculations are shown in the right panel of Figure 2. It is seen that the R(17.05 Å) and R(17.10 Å) line ratios are sensitive to the temperature of the photoexcitation continuum, whereas the R(15.26 Å) and R(15.45 Å) line ratios are not. The R(17.10 Å) line ratio is driven toward zero (the high-density limit) for blackbody temperatures \( T_{bb} \geq 60 \) kK.

To demonstrate the level of sensitivity to photoexcitation of the R(17.10 Å) line, we show in Figure 4 a plot of the R(17.10 Å)/I(17.05 Å) line ratio as a function of density, assuming a plasma temperature \( T_e = 4 \) MK and blackbody temperatures \( T_{bb} = 20, 30, 40, 50, 55, 60 \) kK. The curve for \( T_{bb} = 20 \) kK is virtually identical to the curve without photoexcitation. As the blackbody temperature increases, the line ratio at low densities is seen to first increase slightly and then decrease strongly, approaching the high-density limit for \( T_{bb} \approx 60 \) kK. If the low (17.10 Å)/I(17.05 Å) line ratio observed in EX Hya is due solely to photoexcitation, the blackbody temperature \( T_{bb} \approx 55 \) kK. With \( N_H \approx 10^{20} \text{ cm}^{-2} \), there is no observable flux in the EUV for any of these models, so the only constraint is that they do not produce too much flux in the UV.
the maximum 1010 Å flux density is 2.5 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \ (\text{Mauche} 1999), the fractional emitting area of these hot spots must be \( f \leq 5.8\%, 2.6\%, 2.0\%, \text{ and } 1.5\% \) for \( T_{bb} \approx 40, 50, 55, \text{ and } 60 \text{ kK}, \text{ respectively.} \)

4. SUMMARY AND DISCUSSION

We have shown that the Fe XVII \( I(17.10 \text{ Å})/I(17.05 \text{ Å}) \) line ratio observed in the Chandra HETG spectrum of EX Hya is significantly smaller than that observed in the Sun or other late-type stars. Using LXSS, a new plasma code based on HULLAC atomic data, we find that the observed line ratio can be explained if the plasma density \( n_e \gtrsim 3 \times 10^{14} \text{ cm}^{-3} \). However, if photoexcitation is included in the level-population kinetics, the line ratio can be explained for any density if the photoexcitation temperature \( T_{bb} \gtrsim 55 \text{ kK} \). This latter model is consistent with the assumptions (blackbody emitter, dilution factor equal to \( f \)) and the observed UV flux density only if this hot spot, and the overlying volume of million-degree plasma, covers a very small fraction of the surface area of the white dwarf: \( f \leq 0.02 \). Such a hot spot is smaller and hotter than is usually inferred from optical and UV light curves, but it is possible that the accretion-heated photosphere of the white dwarf contains a range of temperatures, with the required \( T_{bb} \gtrsim 55 \text{ kK} \) spot applying only to that unfortunate piece of real estate lying directly beneath the accretion column. A surrounding larger \( (f \approx 0.1) \) and cooler \( (T_{bb} \approx 37 \text{ kK}) \) suburb might then produce the flux modulations observed at longer wavelengths, but to account for its contribution to the UV flux density, the hottest part of the spot would have to be even smaller. The mean 0.5–10 keV flux of EX Hya during our observation was \( f_X \approx 1 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1} \), and with a white dwarf mass \( M_{wd} = 0.49 M_\odot \ (R_{wd} = 9.8 \times 10^8 \text{ cm}) \) and distance \( d = 100 \text{ pc} \), this implies an X-ray luminosity \( L_X \approx 1 \times 10^{32} \text{ ergs s}^{-1} \), hence a mass-accretion rate \( \dot{M} = 2R_{wd}L_X/GM_{wd} \approx 4 \times 10^{15} \text{ g s}^{-1} \), and hence a post-shock density \( n \geq M/4\pi R_{wd}^2 \mu m_H (v/10)^4/4 \approx 2 \times 10^{14} \text{ cm}^{-3} \) for \( f \approx 0.02 \). Either way, then, the Chandra HETG spectrum of EX Hya requires a plasma density that is orders of magnitude greater than that observed in the Sun or other late-type stars. The Fe XVII \( I(17.10 \text{ Å})/I(17.05 \text{ Å}) \) density diagnostic is useful in sources in which the efficacy of the He-like density diagnostics is compromised by the presence of a bright UV continuum.

We thank H. Tananbaum for the generous grant of Director’s Discretionary Time that made these observations possible. We gratefully acknowledge J. Raymond and N. Brickhouse for ongoing discussions about high-density plasma in EX Hya. P. Beiersdorfer and G. Brown for discussions about Fe XVII. J. Saba for providing the solar Fe XVII line ratios listed in Table 1 and shown in Figure 2, and the referee for a number of suggestions that improved the clarity of the manuscript. C. M. and D. L. were supported in part by NASA Long-Term Space Astrophysics Program grant S-92654-F and NASA Chandra Guest Observer grant NAS 8-39073. This work was performed under the auspices of the US Department of Energy by the University of California Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

REFERENCES

Allan, A., Hellier, C., & Beardmore, A. 1998, MNRAS, 295, 167
Ayres, T. R., et al. 2001, ApJ, 549, 554
Bar-Shalom, A., Klapisch, M., & Oreg, J. 1988, Phys. Rev. A, 38, 1773
Beiersdorfer, P., von Goeler, S., Bitter, M., & Thorn, D. B. 2001, Phys. Rev. A, 64, 032705
Blumenthal, G. R., Drake, G. W. F., & Tucker, W. H. 1972, ApJ, 172, 205
Brown, G. V., Beiersdorfer, P., Liedahl, D. A., Widmann, K., & Kahn, S. M. 1998, ApJ, 502, 1015
Brown, G. V., Beiersdorfer, P., & Widmann, K. 2001, Phys. Rev. A, 63, 032719
Canizares, C. R., et al. 2000, ApJ, 539, L41
Fujimoto, R. & Ishida, M. 1997, ApJ, 474, 774
Gabriel, A. H., & Jordan, C. 1969, MNRAS, 145, 241
Gansecke, B. T., Beurmann, K., & de Martino, D. 1995, A&A, 303, 127
Hellier, C., Mason, K. O., Rosen, S. R., & Cordova, F. A. 1987, MNRAS, 228, 463
Hurtwitz, M., Sirk, M., Bowyer, S., & Ko, Y.-K. 1997, ApJ, 477, 390
Kahn, S. M., et al. 2001, A&A, 365, L312
Kelly, R. L. 1987, Atomic and Ionic Spectrum Lines below 2000 Angstroms: Hydrogen through Krypton (New York: AIP)
Klapisch, M. 1971, Comput. Phys. Comm., 2, 239
Klapisch, M., et al. 1978, Phys. Lett., 69A, 34
Klapisch, M., Schwob, J., Fraenkel, B., & Oreg, J. 1977, J. Opt. Soc. Am., 67, 148
Loulergue, M., & Nussbaumer, H. 1973, A&A, 24, 209
Markert, T. H., et al. 1994, Proc. SPIE, 2280, 168
Mauche, C. W. 1999, ApJ, 520, 822
Mauche, C. W. 2000, BAAS, 32, 1561
Mauche, C. W., et al. 2000, BAAS, 32, 1179
Mazzotta, P., Mazzitelli, G., Colafrancesco, S., & Vittorio, N. 1998, A&AS, 133, 403
Phillips, K. J. H., Greer, C. J., Bhatia, A. K., Coffey, I. H., Barnsley, R., & Keenan, F. P. 1997, A&A, 324, 381
Raymond, J. C., & Smith, B. W. 1986, ApJ, 306, 762
Rosen, S. R., Mason, K. O., & Cordova, F. A. 1988, MNRAS, 231, 549
Rugge, H. R., & McKenzie, D. L. 1985, ApJ, 297, 338
Saba, J. L. R., Schmelz, J. T., Bhatia, A. K., & Strong, K. T. 1999, ApJ, 510, 1064
Smith, B. W., Raymond, J. C., Mann, J. B., & Cowan, R. D. 1985, ApJ, 298, 898
Waldron, W. L., & Cassinelli, J. P. 2001, ApJ, 548, L45