THE DETECTABILITY OF NEON FLUORESCENCE AND MEASUREMENT OF THE SOLAR PHOTOSPHERIC NEON ABUNDANCE

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ABSTRACT

Monte Carlo calculations of the Ne Kα line fluoresced by coronal X-rays and emitted near the temperature minimum region of the solar atmosphere have been employed to investigate the use of this feature to measure directly the solar photospheric Ne abundance. Although very weak, comparison with spectral line databases indicates that at plasma temperatures typical of the quiet Sun and cool active regions ($\lesssim 10^6$ K) the line is isolated and unblended. A canonical solar chemical composition yields an equivalent width of $\sim 6$ mÅ (0.3 eV) when observed at heliocentric angles $\sim 0$. For a 1' field of view, photon fluxes at Earth are of order 0.2 photons s$^{-1}$ for the quiet Sun, rendering the Ne Kα fluorescent line a quite feasible means for determining the solar photospheric Ne content.

1. INTRODUCTION

The abundance of the element neon is notoriously difficult to determine in cool stars like the Sun. Ne exhibits no lines in the visible light spectra of late-type stars, and the solar abundance is based largely on transition region and coronal lines and energetic particle measurements, supplemented with local cosmic estimates (e.g., Meyer 1985; Anders & Grevesse 1989). The Ne abundance is usually measured relative to that of O (Landi et al. 2007; see, however, the recent Ne/H measurement of Landi et al. 2007). While the majority of past solar Ne/O estimates (see the supplementary data in Drake & Testa 2005), together with recent analyses of Solar Maximum Mission (SMM) and Solar and Heliospheric Observatory archival spectra (Schmelz et al. 2005; Young 2005), support the canonical ratio of 0.15 by number (e.g., Anders & Grevesse 1989; Asplund et al. 2005), there is a scatter of measurements around this value by more than a factor of 2—even among measurements of different solar regions made with the same instrumentation (McKenzie & Feldman 1992; Strong et al. 1988). Based on an analysis of X-ray He-like Ne and H-like O resonance lines McKenzie & Feldman (1992) concluded that the Ne abundance must vary in the solar corona.

Faced with the prospect of coronal Ne fractionation by a process that is not yet firmly identified or understood, it is not clear that the neon content of any region of the solar outer atmosphere will be the same as that of the deeper layers.

The solar neon content represents a potentially large source of uncertainty for understanding the oscillation spectrum of the Sun. Models employing a recently advanced solar chemical composition based on three-dimensional (3D) non-LTE hydrodynamic photospheric modeling (Asplund et al. 2005) lead to predictions of the depth of the convection zone, helium abundance, density, and sound speed in serious disagreement with helioseismology measurements (Basu & Antia 2004; Bahcall et al. 2005a). The Asplund et al. (2005) mixture contains less of the elements C, N, O, and Ne that are important for the opacity of the solar interior by 25%–35% compared to earlier assessments (e.g., Anders & Grevesse 1989; Grevesse & Sauval 1998). Antia & Basu (2005) and Bahcall et al. (2005b) suggested the uncertain solar Ne abundance might be raised to compensate. While enthusiasm for this solution has been dampened by a study of solar parameter uncertainties inferred from oscillation data that appear to exclude such large Ne abundance revisions (Delahaye & Pinsonneault 2006), Drake & Testa (2005) found empirical support from Chandra high-resolution X-ray spectra of mostly magnetically active stars for which the Ne/O abundance ratio appears consistently higher by a factor of $\sim 2$ or more than the currently recommended solar value of $Ne/O = 0.15$ by number.

In this Letter we examine the possibility of using the Ne Kα X-ray line of neutral Ne at 14.61 Å (0.849 keV) to measure the photospheric Ne abundance. While undoubtedly very weak compared with the lines of highly ionized Ne formed in the transition region and corona, the Ne Kα line is formed by inner-shell photoionization by coronal X-rays of Ne near the temperature minimum region of the solar atmosphere (Drake & Ercolano 2007), beneath the chromospheric zone where chemical fractionation processes related to element first ionization potential (FIP) are thought to occur (e.g., Meyer 1985; Feldman 1992). We present Monte Carlo calculations of the fluorescent Ne Kα line in § 2, and discuss its observability in §§ 3 and 4.

2. MONTE CARLO CALCULATIONS OF NEON FLUORESCENCE

The X-ray Ne “characteristic” (fluorescence) Kα line at 14.61 Å (Bearden 1967) corresponds to the $2p$–$1s$ decay of the excited state resulting from ejection of an inner-shell 1s electron in neutral or near-neutral neon by either electron impact or photoionization. In the case of the solar photosphere illuminated from above by coronal X-rays, fluorescent lines will be produced almost entirely by photoionization (Basko 1978; Bai 1979; Parmar et al. 1984). Bai (1979) pointed out that, for a given source spectrum, $F(\lambda)$, the observed flux of Kα photons from the photosphere depends on essentially three parameters: the photospheric abundance $A$ of the fluorescing species relative to that of other elements of significance for the photoabsorption opacity in the vicinity of the 1s ionization edge; the height $h$ of the emitting source; and the heliocentric angle $\theta$ between the emitting source and the observer.

Fluorescent lines are formed in the region of an atmosphere corresponding to optical depth unity for the primary K-shell ionizing photons. Drake & Ercolano (2007) showed that in the case of the fluorescent lines from abundant elements O–Fe formed in the solar atmosphere, this occurs below the chromosphere. For the case of Ne the solar atmospheric model C (VALC) of Vernazza et al. (1981) indicates that the K-shell $\tau = 1$ depth occurs at a gas temperature of about 5000 K, just
of coronal isothermal plasma temperatures in the range 10^6–10^7 K.

incident packet of frequency \( n \) threshold (870 eV) is immediately followed by reemission of by Ne of a packet with energy above the K-shell ionization absorption or Compton scattering, the probabilities of which are including Ne, are neutral. Energy packets can undergo photoab-

sume the photosphere to be "cold," whereby all elements, in-

overlying corona and are incident on the photosphere. We as-

monochromatic energy packets that sample the spectrum of the work for further details.

K fluorescence is similar to that for Fe K and we describe our code has been tested in detail for Fe K transitions within the 5

line we used a modified version of the 3D Monte Carlo radiative code MOCASSIN (Ercolano et al. 2003, 2005). This

line for a Ne abundance elevated by a factor of 3 (Ne/H = 8.58, or [Ne/H] = 0.5). The calculated Ne Kα flux is sensitive to the chemical mixture in the photosphere, but is also sensitive to some extent to that assumed for the coronal spectrum through the contribution to the ionizing flux from lines (see § 3.1). Coronal spectra were computed using emissivities from the CHIANTI database (ver. 5.2; Dere et al. 1997; Landi et al. 2006) and the ion populations of Mazzotta et al. (1998) as implemented in the PINTofALE IDL suite of programs (Kashyap & Drake 2000).

Fig. 1.—**Top:** Strength of the Ne Kα line (black) shown in comparison to neighboring and blending lines (gray) in the fluorescing coronal X-ray spectrum in units of 10^{-35} erg cm^{-2} s^{-1} bin^{-1} (with bins of size 8.6 \times 10^{-4} Å) for coronal isothermal plasma temperatures in the range 10^6–10^7 K. **Bottom:** Same coronal spectra with (solid curves) and without (dashed curves) the addition of Ne Kα smoothed to a resolving power (FWHM) of \( \lambda/\Delta\lambda = 1000 \).

above the temperature minimum and about 700 km above the point where the continuum optical depth at 5000 Å, \( \tau_{5000} \) is unity.

To estimate the expected intensity of the emergent Ne Kα line we used a modified version of the 3D Monte Carlo radiative transfer code MOCASSIN (Ercolano et al. 2003, 2005). This code has been tested in detail for Fe Kα photospheric fluorescence problems by comparison with the computations of Bai 1979 (1979; see Drake & Ercolano 2007). Computation of Ne K fluorescence is similar to that for Fe K and we describe our method here only in brief; the reader is referred to the earlier work for further details.

The fluorescence calculation involves following the fate of monochromatic energy packets that sample the spectrum of the overlying corona and are incident on the photosphere. We assume the photosphere to be "cold," whereby all elements, including Ne, are neutral. Energy packets can undergo photoabsorption or Compton scattering, the probabilities of which are determined by the respective cross sections. Photoabsorption by Ne of a packet with energy above the K-shell ionization threshold (870 eV) is immediately followed by reemission of \( n \) of Ne Kα packets from the same event location. For an incident packet of frequency \( \nu \), carrying energy \( E_0 \) in the unit time \( \Delta t \) the total Ne Kα emission is given by

\[
L(\text{Ne Kα}) = nL(\text{Ne Kα}) = n \frac{E_0}{\Delta t} \frac{\kappa_{\text{Ne}} Y_{\text{Ne Kα}} E_{\text{Ne Kα}}}{\kappa_\nu R_0},
\]

where \( \kappa_{\text{Ne}} \) and \( Y_{\text{Ne Kα}} \) are the absorption opacity and the Ne Kα yield, \( E_{\text{Ne Kα}} \) is the energy of the Kα line (\( \sim 0.848 \) keV), \( \kappa_\nu \) is the absorption opacity due to all other abundant species, and \( R_0 \) is the branching ratio between Kα and Kβ fluorescence (0.882 : 0.118; Bambeynek et al. 1972). We adopted a value of 0.018 for the fluorescence yield of neutral neon (Krause 1979).

The fates of Ne Kα packets are then determined by the absorption and Compton opacities encountered along their diffusion paths. Emergent integrated and direction-dependent spectral energy distributions are determined from the packets that escape the photosphere. For a given coronal X-ray spectrum, the maximum intensity of a fluorescent line is achieved for a heliocentric angle \( \theta = 0 \) and coronal height \( h = 0 \). Since we are primarily interested here in whether the line is observable or not, we adopt these as baseline parameters in order to estimate the maximum possible strength of the line.

The Ne Kα flux was computed for isothermal irradiating coronal spectra with plasma temperatures in the range 10^6–10^7 K and the chemical composition of Grevesse & Sauval (1998) with Ne/H = 8.08 on the usual log +12 scale. We also performed calculations for a Ne abundance elevated by a factor of 3 (Ne/H = 8.58, or [Ne/H] = 0.5). The calculated Ne Kα flux is sensitive to the chemical mixture in the photosphere, but is also sensitive to some extent to that assumed for the coronal spectrum through the contribution to the ionizing flux from lines (see § 3.1). Coronal spectra were computed using emissivities from the CHIANTI database (ver. 5.2; Dere et al. 1997; Landi et al. 2006) and the ion populations of Mazzotta et al. (1998) as implemented in the PINTofALE IDL suite of programs (Kashyap & Drake 2000).

3. STRENGTH OF THE Ne Kα LINE

3.1. Monte Carlo Results

Model spectra corresponding to the combination of coronal direct and photospheric reprocessed X-rays seen by an observer at \( \theta = 0 \) in the vicinity of the Ne Kα line are illustrated for a range of coronal temperatures in Figure 1. Also shown are the same spectra seen at a resolving power of \( \lambda/\Delta\lambda = 1000 \), where \( \Delta\lambda \) is assumed to be the full width at half-maximum of a Gaussian instrument response function.

From Figure 1 it is apparent that the Ne Kα line coincides rather closely with a weak line of Fe xviii at 14.61 Å. While absent at quiescent plasma coronal temperatures found in the Sun of (1–2) \times 10^6 K, this line becomes problematic for temperatures significantly above this range, such as might be found in active regions or flaring conditions. The full list of lines in the CHIANTI version 5.2 database within 5 \( \sigma \) (±0.031 Å) of Ne Kα are listed in Table 1. The NIST Atomic Spectra Database (ver. 3.1.2;Ralchenko et al. 2007) also lists eight other transitions within the 5 \( \sigma \) range from the highly ionized iron-group elements Ti, V, Cr, and Co. The brighter lines of Ti and Cr are included in the CHIANTI database, and owing to the low cosmic abundance of these four elements (300, 3000, 70, and 380 times less abundant than Fe, respectively; Grevesse & Sauval 1998) we do not anticipate any of these transitions to be of significant strength compared with the Fe lines or Ne Kα.

A fiducial for the observability of a spectral line can be expressed in terms of its equivalent width. In the case of lines excited by fluorescence, this equivalent width is most usefully related to the ionizing coronal spectrum against which it will
be observed, as illustrated in Figure 1. We have calculated this quantity for each of the models in our grid, for Ne abundances equivalent to the Grevesse & Sauval (1998) value and for 3 times this ([Ne/H] = 0 and [Ne/H] = 0.5); results are illustrated in Figure 2. Also shown is the equivalent width for the Fe xviii blend. Since the Ne and Fe xviii lines are coincident, the resolving power required to separate them can be considered both out of reach of foreseeable instrumentation and physically infeasible owing to thermal broadening that will irretrievably smear the lines together. Nevertheless, at cooler coronal temperatures the blend is negligible and Ne Kα should be the only significant spectral feature in the vicinity.

We conclude that Ne Kα is in principle quite observable and isolated in high-resolution spectra with sufficient signal-to-noise ratio (S/N) to detect the line above the continuum, provided plasma temperatures are lower than 2.5 × 10^5 K. If the strength of the blending Fe xviii line can be accurately modeled, the useful temperature range of Ne Kα measurements could extend to ~3 × 10^6 K.

### Table 1

| Ion | λ (Å) | Rel. Int. | log T_{\text{min}} | Transition |
|-----|-------|-----------|---------------------|------------|
| Fe xviii | 14.584 | 1.0 | 6.90 | 2s^2p^6 3P_2–2s^2p^5 (P)3d^1 P_{3/2} |
| Fe xix | 14.596 | 2.5 × 10^{-4} | 6.90 | 2s^2p^6 1P_1–2s^2p^5 (P)3d^1 P_{1/2} |
| Fe xix | 14.600 | 1.2 × 10^{-4} | 6.90 | 2s^2p^6 3P_2–2s^2p^5 (P)3d^1 P_{3/2} |
| Fe xviii | 14.610 | 0.40 | 6.85 | 2s^2p^6 3P_2–2s^2p^5 (P)3d^1 P_{3/2} |
| Fe xix | 14.622 | 0.03 | 6.90 | 2s^2p^6 1P_1–2s^2p^5 (D)3s^1 D_{5/2} |
| Fe xix | 14.628 | 0.01 | 6.90 | 2s^2p^6 3P_2–2s^2p^5 (D)3s^1 D_{3/2} |
| Fe xx | 14.633 | 1.2 × 10^{-3} | 7.0 | 2s^2p^6 3P_2–2s^2p^5 (P)3s^1 P_{3/2} |

### 3.2. Existing Solar Spectra of the Ne Kα Region

There have been no recent high resolution X-ray spectra taken in the 14–15 Å range of the solar corona. The most extensive set of observations dates back to the SMM Flat Crystal Spectrometer (FCS; Acton et al. 1980). Owing to the limited detector form factors available, this was a scanning instrument in which only a small fraction of the spectrum could be recorded at a time, limiting the exposure and S/N attainable for a given wavelength. In this context, it is important to realize that much higher quality spectra could be obtained with current technology. Indeed, it is by no means an exaggeration to note that spectra of this region obtained for much more distant cosmic X-ray sources by the Chandra X-Ray Observatory are now routinely of similar or higher spectral quality than those that have been obtained to date for the nonflaring Sun.

FCS spectra covering our spectral range of interest for cooler solar active regions have recently been analyzed by Schmelz et al. (2005), who selected 20 of the highest S/N spectra in the ~13–20 Å range (FCS channel 1), obtained in 1986–1987, in which Fe xix emission was not visible. Since these selection criteria are not too dissimilar to our requirements for seeing unblended Ne Kα, we have examined the same set of spectra obtained from the FCS archive, summed in order to realize the maximum possible S/N. The resulting spectrum is illustrated in Figure 3. An Fe xviii line at 14.20 Å is clearly visible in these spectra: the intensity of the blending Fe xviii line at 14.61 Å can be put in context by noting that the CHIANTI emissivity ratio for these lines is 52 : 1.

Unfortunately, the FCS spectra suffer from quite severe background contamination due to fluorescence in the spectrometer crystals (Phillips et al. 1992). At the resolution of the FCS channel 1, corresponding to a resolving power of ~1000, our synthetic coronal spectra have peak line-to-continuum flux density ratios of order 10^3 for the strong Fe xvii λ15.01 line for temperatures (2–3) × 10^6 K. In the summed FCS spectrum in Figure 3, the line peaks at 1.3 × 10^{-2} in the same relative flux density units. The background continuum in this spectral region is about 1.05 × 10^{-3}, or ~2 orders of magnitude larger than the plasma thermal continuum. At the same spectral resolution, a line with intensity corresponding to our computed Ne Kα equivalent widths—of order 0.35 eV or 6 mÅ for a coronal temperature of 2 × 10^6 K—would have a peak intensity of order 50% of the thermal continuum intensity; the line is completely swamped in the FCS by the crystal fluorescence background.

### 3.3. Observability of Ne Kα Fluorescence

From the above, it is apparent that detection of the Ne Kα line requires much greater instrumental sensitivity than afforded by the SMM FCS. The temperature range in which the line remains blend-free and isolated is typical of those found in the

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**Fig. 2.—Equivalent width of the Ne Kα line with respect to the ionizing coronal X-ray spectrum as a function of isothermal plasma temperature, computed for 1 and 3 times the photospheric Ne abundance of Grevesse & Sauval (1998). Also shown is the equivalent width of the Fe xviii line that blends with the Ne feature. The different y-axes are labeled in Å and eV units.

**Fig. 3.—SMM FCS channel 1 spectrum in the region of the Ne Kα line obtained from combining 20 different observations of cooler active regions. The full channel 1 spectrum is shown inset.**
coolest active regions and in the quiet Sun. Quiet-Sun X-ray surface fluxes are of order $10^3$ ergs cm$^{-2}$ s$^{-1}$ (e.g., Withbroe & Noyes 1977). Our model coronal X-ray spectra at a temperature $T\sim 1.5 \times 10^6$ K scaled to this surface flux and covering, for example, a $1' \times 1'$ field of view corresponds to a flux density in the continuum at 14.61 Å of about 30 photons s$^{-1}$ Å$^{-1}$, and a Ne Kα flux of $\sim 0.2$ photons s$^{-1}$. High-resolution imaging would not be required for a useful Ne Kα measurement, and such a flux level is in principle easily observed. The large intensity contrast between Ne Kα and neighboring strong lines, such as Fe xvii λ15.01, does, however, impose tight instrumental profile requirements in order to avoid spill-over contamination. This requirement could be eased by adopting a narrowband filter to attenuate neighboring strong lines.

The feasibility of observing Ne Kα also depends critically on the absence of blending lines. The veracity of current line lists in the immediate vicinity of Ne Kα should be investigated further using appropriate computational and laboratory surveys in order to evaluate the current assessment that the line is unblended at quiet Sun coronal temperatures.

4. CONCLUSION

We have investigated the observability of the Ne Kα line by means of 3D Monte Carlo calculations using the MOCassin code. Resulting line fluxes are similar to those of the underlying continuum of the fluorescing spectrum. While very faint compared to the prominent lines of abundant coronal ions, Ne Kα should be essentially unblended at typical quiet Sun temperatures, but will become catastrophically blended with a line of Fe xviii at significantly higher temperatures. We estimate an Ne Kα flux of $\sim 0.2$ photons s$^{-1}$ for a $1'$ field of the quiet Sun at heliocentric angles close to 0°. Such a flux is easily observed, and the Ne Kα fluorescent line would seem to represent a feasible means to measure the photospheric Ne abundance.

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