MEASUREMENTS OF THE f-VALUES OF THE RESONANCE TRANSITIONS OF Ni ii AT 1317.217 AND 1370.132 Å

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ABSTRACT

We have retrieved high-resolution UV spectra of 69 hot stars from the HST archive and determined the strengths of the interstellar Ni ii absorption features at 1317.217 Å arising from the ground 3d⁰ ⁴D₃/₂ electronic state to the 3d⁸ (1G) ⁴P₂ ⁴F₉/₂ excited level. We then compared them to absorptions to either the 3d⁸ (3F) ⁴P₂ ⁴D₃/₂ or 3d⁸ (3P) ⁴P₂ ⁴F₉/₂ upper levels occurring at, respectively, λ = 1741.553 Å (covered in the spectra of 21 of the stars) and 1370.132 Å (seen for the remaining 48 stars). All spectra were recorded by the either the E140M, E140H, or E230H gratings of the Space Telescope Imaging Spectrograph. By comparing the strengths of the two lines in each spectrum and evaluating a weighted average of all such comparisons, we have found that the f-value of the 1317 Å line is 1.34 ± 0.019 times the one at 1741 Å, and 0.971 ± 0.014 times the one at 1370 Å. We adopt as a comparison standard an experimentally determined f-value for the 1741 Å line (known to 10% accuracy), so that f(1317) = 0.0571 ± 0.006. It follows from this f-value and our measured line-strength ratios that f(1370) = 0.0588 ± 0.006. As an exercise to validate our methodology, we compared the 1317 Å transition to another Ni ii line at 1454.842 Å to the 3d⁸ (1D) ⁴P₂ ⁴D₃/₂ level and arrived at an f-value for the latter that is consistent with a previously measured experimental value to within the expected error.

Subject headings: atomic data — ultraviolet: ISM

1. INTRODUCTION

For investigations of the interstellar gases in either our Galaxy or distant systems in the universe, nickel belongs to a class of elements that is usually strongly depleted onto dust grains (Savage & Sembach 1996; Jenkins 2004), but also represents the important iron-peak group that is synthesized mostly by Type Ia supernovae at later stages in a galaxy’s chemical evolution (Wheeler et al. 1989; McWilliam 1997). For neutral regions having N(H i) ≥ 10¹⁰.⁵ cm⁻², most of the Ni atoms should be in the singly ionized form. Numerous Ni ii lines with differing strengths in the wavelength interval 1300 < λ < 1900 Å are well suited for deriving column densities of singly ionized Ni using a curve of growth. Other Fe group elements such as Cr, Mn, Fe, Co, and Zn also exhibit two or more moderately strong lines for their most abundant, singly ionized forms, but most of the useful features are at λ > 2000 Å in the rest frame, a wavelength range that might not be covered by some observations. (A few lines of Cu ii at shorter wavelengths are usually too weak to observe.)

In the recent compilation by Morton (2003) of UV and visible transitions out of the ground electronic states of various atoms, experimentally determined f-values are listed for 14 different transitions of Ni ii, with numerical values that range from 0.001 to 0.08,² based on the laser-induced fluorescence lifetime measurements of Fedchak & Lawler (1999) for a few of them, with extensions to the remaining ones using relative absorption strengths measured in the laboratory by Fedchak et al. (2000) and supplemented by Hubble Space Telescope (HST) recordings of absorption lines measured by Zsargó & Federman (1998).³ These measurements have made some important improvements in the f-values of different Ni ii transitions and have resolved some earlier apparent anomalies in the abundance ratios of Ni to Fe in various distant gas systems (Howk et al. 1999). Finally, theoretical calculations of the transition probabilities for the 3d⁸–3d⁸ ⁴P₂ and 3d⁸ ⁴S₄–3d⁸ ⁴P₂ transition arrays of Ni ii have been carried out by Fritzsche et al. (2000).

One transition that has not yet been investigated experimentally is the 3d⁰ ⁴D₃/₂ → 3d⁸ (1G) ⁴P₂ ⁴F₉/₂ line of Ni ii at 1317.217 Å. As we show below, this line has a strength about equal to those of the strongest lines of Ni ii at 1370.132 and 1741.553 Å to the upper-level configurations 3d⁸ (3P) ⁴P₂ ⁴D₃/₂ and 3d⁸ (3F) ⁴P₂ ⁴D₃/₂. For extragalactic systems that have only enough Ni ii to allow a detection using either the 1370 Å line or the one at 1741 Å, the usefulness of these lines might be compromised in some circumstances by either restrictions in the wavelength coverage or possible interference from random lines from the Lyα forest when zₑₜ < zₑₚ. Thus, having a redundant feature with about the same strength at a different wavelength provides a useful alternative to help overcome these limitations.

¹ Based on observations from the NASA/ESA Hubble Space Telescope obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.
² Many more 3f-values for Ni ii were listed in Morton’s (1991) earlier survey of resonance lines, but these values were based on the approximate theoretical 3f-values of Kurucz (communicated privately to Morton). In his publication of 2003, Morton chose not to list these 3f-values because they had a much lower accuracy than the experimental values.
³ Zsargó & Federman (1998) measured relative 3f-values and scaled them according the old values for other Ni ii lines given in Morton (1991). Later, Fedchak & Lawler (1999) recommended that those 3f-values should be scaled downward by a factor of 0.534, on the basis of changes in the 3f-values indicated for comparison transitions at longer wavelengths. Morton’s (2003) compilation has adopted the 3f-values of Zsargó & Federman (1998) with this reduction factor.
The strength of the transition at 1370 Å has not been measured in the laboratory, but Zsargó & Federman (1998) have compared interstellar features for this line to those seen at longer wavelengths for which laboratory data now exist (their original study made use of the less accurate \( f \)-values given in Morton 1991). This comparison, however, was performed for only two velocity components appearing in the spectrum of a single star (\( \zeta \) Oph), and the interpretations of these mildly saturated lines made use of curves of growth for velocity parameters \( b \) derived from the lines of other species (Savage et al. 1992). Thus, while the \( f \)-value of the 1370 Å line has been determined astrophysically, it is reasonable to expect an improvement in accuracy if more interstellar line data can be obtained.

Our objective of this study is to gather high-resolution spectra of hot stars from the HST archive and compare the strengths of the interstellar absorption features from Ni ii at wavelengths 1317, 1370, and 1741 Å. The line at 1741 Å will be used as our fundamental comparison standard, since its \( f \)-value has been measured in the laboratory (Fedchak & Lawler 1999) and thus is relatively trustworthy. An important feature of our comparisons is that the near similarity of line strengths for any given target star makes our interpretations relatively immune to poorly understood saturation effects, since such effects, if they exist, will have roughly equal strengths for all three lines and thus will not affect the ratios that we calculate. The spectra that we use contain either the line pair 1317 and 1370 Å, or the pair 1317 and 1741 Å. Thus, we are not able to directly compare the 1370 Å line to the one at 1741 Å, but instead we must link it to the line at 1371 Å.

A similar determination of the relative Ni ii \( f \)-values was carried out by Ellison et al. (2001) using a spectrum of a damped Ly\( \alpha \) system in front of a quasar. We expect that our comparison should be more accurate, since we are using many spectra with high S/N. Also, in many cases our spectral resolution is much higher, which makes it much less likely that we could be misled by the effects of narrow, saturated velocity components.

2. DATA

For our study of the absorption pairs at 1317 and 1741 Å, we used spectroscopic data for 21 stars gathered from our earlier study of C i absorption features (Jenkins & Tripp 2001) that employed the E140H and E230H echelle gratings of the Space Telescope Imaging Spectrograph (STIS) on HST (observing programs 8043 and 8484). The design and performance of STIS have been discussed by Woodgate et al. (1998) and Kimble et al. (1998). The spectra had resolving powers \( \lambda/\Delta \lambda = 200,000 \) because they were recorded with a very narrow entrance slit on the spectrograph (0′′1 × 0′′03), and the detector was read out with twice the normal spatial sampling rate. We described in a previous article (Jenkins & Tripp 2001) the special data reduction techniques that we used to preserve the high spectral resolution without showing a high-frequency signal caused by a sensitivity imbalance of adjacent Hi-Res pixels of the STIS MAMA detector. For the 1741 Å line, we could combine the recordings in two adjacent echelle orders to increase the signal-to-noise ratio. To show the quality of the spectra, in Figure 1 we present some examples of the E140H and E230H data that we used.

The observations by Jenkins & Tripp (2001) did not cover the Ni ii line at 1370 Å, so an entirely separate collection of observations was used to compare the 1317 Å transition to the one at 1370 Å. Most of the data were taken from Snapshot (SNAP) observations of many stars in the Milky Way (program IDs 8241, 8662, 9434 initiated by J. Lauroesch) that are held in the MAST archive at the Space Telescope Science Institute, with a few additional targets from the observations taken for programs 7137, 7270, 7301, and 8487. The spectra were recorded for 48 different stars using the E140H and E140M gratings with wavelength resolving powers \( \lambda/\Delta \lambda = 110,000 \) and 45,800, respectively (Kim Quijano et al. 2003). A subset of these stars was used for a validation exercise with another Ni ii line at 1454 Å, discussed in \( \S \) 3.4.

For all of the spectra in both studies, the Ni ii features were always visible, with equivalent widths that ranged from 8 to 140 mA. The signal-to-noise ratios (S/N per pixel)\(^4\) ranged from 18 to 50 (Fig. 1 shows spectra with S/N \( \simeq 30 \)). For the star with the weakest lines, the equivalent widths of the Ni ii lines were at least 3 times their respective 1 \( \sigma \) uncertainties. We restricted our investigation to stars with large projected rotation velocities, \( v \sin i \), in order to avoid ambiguous continuum placement problems and blending with stellar lines. In a few cases, velocity components that were well separated from each other could be measured separately.

\(^4\) Multiply by \( \sqrt{2} \) to obtain the S/N per resolution element.
3. ANALYSIS

3.1. General Considerations

We fitted continua to the spectra using least-squares fits to Legendre polynomials in places that were free of spectral features, following the methods outlined by Sembach & Savage (1992). Errors in line strength caused by continuum uncertainties can be evaluated from the error matrix for the polynomial coefficients, but we have found from past experience that it is wise to multiply these uncertainties by 2 to allow for certain arbitrary assumptions, such as the choice of wavelengths over which the intensities are used to define the continuum. Another source of error is the uncertainty of photon counts within the absorption line, as indicated by the STIS intensity error vector. This error should be independent of the one related to the continuum uncertainty. Hence, we could add the two in quadrature to evaluate the overall uncertainty in the measurement. For one of our line pair comparisons (1317 vs. 1370 Å), we found that the magnitudes of the apparent random deviations away from a simple relationship between the overall line strengths was slightly larger than expected, indicating that additional small errors are probably present. (We return to this issue below.) A reasonable interpretation for these additional errors is that they arise either from variations in the detector sensitivity (i.e., "fixed pattern noise") that were not fully corrected, or from inaccurate scattered-light corrections.

For weak lines in the presence of noise, it is important to impose rigid constraints on the wavelength limits for the measurement. Otherwise, we may introduce errors in the comparison if the limits changed from one line to the next, and moreover, systematic biases in the measurements can arise if the lines’ own appearances are used as guides for the end points (Joseph 1989). Thus, we defined the velocity limits for interstellar material along each line of sight using the S i line at 1250.578 Å. This line is usually much stronger than the Ni ii line, so that it is easier to see the full extent of the absorptions above the noise, but not so strong that small, irrelevant wisps of high-velocity material cause an unnecessary consideration of the more extreme velocities. Another advantage in using a strong line to define the velocity limits is that we can be more certain that the continuum definition occurs at wavelengths that are fully outside the region where any absorption might occur. The principle invoked here for defining the velocity limits from the S ii feature is illustrated in Figure 1.

To simplify our comparison of line strengths, we compute the apparent optical depths \( \tau_a(\nu) = \ln[I_{\text{cont}}(\nu)/I(\nu)] \) over all relevant velocities \( \nu \) within the absorption feature (Savage & Sembach 1991). The ratios of these quantities at any velocity for two lines should indicate the relative values of \( f/\lambda \), provided there are no narrow, unresolved structures that are saturated within the profiles (Savage & Sembach 1991; Jenkins 1996). The largest value of \( \tau_a(\nu) \) that we ever found was 1.4, which means that at no point in any of the spectra were the lines heavily saturated.

3.2. The \( f \)-Value of the 1317 Å Line

Figure 2 shows comparisons in different spectra of the apparent optical depths for the 1317 and 1741 Å lines, integrated over velocity, i.e., \( \tau_a, \text{int}(1317) = \int \tau_a(\nu)d\nu \). It is clear from this figure that the 1317 Å line has about the same strength as the one at 1741 Å. From the fact that all measurements fall very near a single diagonal line with a unit slope in this diagram, it is evident that stars with strong Ni ii lines do not show a ratio of line strengths that is appreciably different from cases showing much weaker features. This increases our confidence that we are not being misled by unrecognized saturation effects.

Our best determination for \( R \), a quantity that we designate as the logarithm of the value of \( f/\lambda \) for the 1317 Å transition divided by that for the 1741 Å transition, was derived from a weighted mean of the individual differences in the logarithms of the integrated apparent optical depths,

\[
R = \frac{\sum [\log \tau_{a,\text{int}}(1317) - \log \tau_{a,\text{int}}(1741)] W_i}{\sum W_i},
\]

(1)

where each weight \( W_i \) is given by the inverse square of the error of each comparison,

\[
W_i = \left( \frac{\sigma[\log \tau_{a,\text{int}}(1317)]^2 + \sigma[\log \tau_{a,\text{int}}(1741)]^2}{2} \right)^{-1},
\]

(2)

with \( \sigma[\log \tau_{a,\text{int}}(1317) \text{ or } 1741] \) being the uncertainty of the respective \( \log \tau_{a,\text{int}} \) value arising from the combination of continuum and photon counting errors. Using equations (1) and (2) we find that

\[
R = +0.005 \pm 0.006 \text{ dex}.
\]

Our determination of \( \chi^2 = 22.1 \) for 20 degrees of freedom seems reasonable, indicating that our formally derived errors are probably correct. The formal uncertainty for \( R \) given in equation (3) was derived from the expression \( \sigma(R) = (\sum W_i)^{-0.5} \).

To determine the \( f \)-value of the 1317 Å transition, we take the product of \( f(1741) = 0.0427 \) measured by Fedchak et al. (2000) and listed by Morton (2003), 10\( ^5 \), and the ratio of wavelengths (1741/1317) to obtain \( f(1317) = 0.0571 \). Our value for \( \sigma(R) \) is much smaller than the probable uncertainty of 0.04 dex estimated by Fedchak et al. (2000) for the value of \( f(1741) \), which served as our comparison standard. This error thus dominates the relative uncertainty of the \( f \)-value of the 1317 Å line.

3.3. The \( f \)-Value of the 1370 Å Line

Now that we have derived our value for \( f(1317) \), we can use our other set of observations that had both the 1317 and 1370 Å
Fig. 3.—Comparison of the logarithms of the integrated apparent optical depths \( \int \tau_\text{a}(\nu) d\nu \) for the 1317 and 1370 Å lines for 48 different stars. The inner ticks on the error bars indicate the originally computed uncertainties, while the outer ones show the artificially increased errors needed to make the \( \chi^2 \) values roughly equal to the number of degrees of freedom. Two trend lines are shown: the dashed line shows the locus of equal line strengths, while the solid line indicates where the transitions have a logarithmic difference of strengths \( R = -0.030 \) dex. As with the data shown in Fig. 2, eqs. (1) and (2) were used to evaluate \( R \), but with the designations 1741 being replaced by 1370.

features to derive \( f(1370) \). Figure 3 shows our comparison of these two lines, in the same style as Figure 2. Again we use equations (1) and (2) (but this time replacing the 1741 for 1370 Å) to derive \( R = -0.031 \) dex, with \( \sigma(R) = 0.004 \) dex.

Unlike what we found in our study of the 1317/1741 line pairs, here there were indications that our calculated line measurement errors slightly underestimated the true ones, since we found that \( \chi^2 = 70.1 \) for 51 degrees of freedom.\(^6\) To properly acknowledge that the scatter of the results exceeded our initial expectations, we created an additional, ad hoc error term \( \sigma(\text{extra}) = 0.5 \) km s\(^{-1} \) that we felt should be factored into our determinations of \( \tau_\text{a, int} \). The square of this term was added to the sums of the squares of the errors attributable to just the deviations caused by continuum and noise uncertainties, so that the value of \( \chi^2 \) was ultimately reduced to about 50. With these slightly larger errors, the reevaluation of equations (1) and (2) gave our final result,

\[
R = -0.030 \pm 0.006 \text{ dex.} \tag{4}
\]

In a calculation similar to the one for the 1317 Å line, we now evaluate the product of \( f(1317) = 0.0571 \) that we found earlier (§ 3.2), \( 10^{-5} \), and the wavelength ratio to obtain \( f(1370) = 0.0588 \). By combining the errors in the determinations of the two values of \( R \) that must be used (the ones in eqs. [3] and [4]) to link ultimately to the \( f \)-value of the 1454 Å line, we obtain a formal relative uncertainty of 0.009 dex, which once again is small compared to the 10% error in the comparison line.

3.4. Validation of Our Method Using the 1454 Å Line

The strength of the \( \text{Ni} \, \Pi \) transition to the \( 3d^8 (1D) 4p^2 \Delta^2 S^2 \) level at 1454.842 Å has been determined by Fedchak et al. (2000), although only to an accuracy of 25% (0.12 dex). As a demonstration, we can repeat the analysis that we performed in § 3.3 for this line, so that we can gain some assurance that our comparison method is sound. In fact, this test is more demanding than the actual studies that we carried out, since the strength of the 1454 Å is substantially less than those of the other three lines.

Figure 4 shows our comparison of the 1317 and 1454 Å lines, in the same style as in Figures 2 and 3. For these data, once again we used equations (1) and (2) (replacing the 1741 Å line with 1454 Å) to obtain

\[
R = 0.298 \pm 0.012 \text{ dex,} \tag{5}
\]

which yielded \( \chi^2 = 16.7 \) for 23 degrees of freedom. From the above value of \( R \), we infer from a repeat of the calculations discussed previously that \( f(1454) = 0.0260 \pm 0.0026 \). This result is consistent with the value 0.0323 ± 0.008 derived by Fedchak et al. (2000) to within their stated errors.

4. SUMMARY

In acknowledging the importance of deriving gas-phase abundances of Ni in various astrophysical systems, we have recognized a need for deriving an \( f \)-value for the \( \text{Ni} \, \Pi \) transition at 1317 Å, as well as the desirability of obtaining an improved accuracy for the \( f \)-value of the line at 1370 Å. In pursuing the first of these two goals, we have compared the integrated apparent optical depths \( \tau_\text{a, int} = \int \tau_\text{a}(\nu) d\nu \) of interstellar \( \text{Ni} \, \Pi \) absorption features at 1317 Å to those of their counterparts 1741 Å seen in high-resolution spectra of 21 stars recorded by STIS on \( \text{HST} \). Since the \( f \)-value of the 1741 Å line has been determined by laboratory measurements to a good accuracy (10%), it can serve as a comparison standard for the 1317 Å line. We have deliberately avoided trying to compare the 1317 Å transition to other, weaker ones, so that we can bypass the uncertainties that are created by possible unresolved, saturated structures within the line profiles. Nevertheless, the success of our demonstration given in § 3.4 shows that our method works satisfactorily even when there is a moderately large disparity of line strengths. We used the strong profiles of \( \text{S} \, \Pi \) absorptions at 1250 Å to define the velocity endpoints of the \( \text{Ni} \, \Pi \) profiles, which on some occasions were difficult to measure.

Our analysis indicated that \( f(1317) = 0.0571 \pm 0.006 \), where the error is dominated by the uncertainty in the \( f \)-value of the comparison line. It is important to note that this value is only

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\(^6\) While only 48 stars were measured, four of them had extra, well-separated velocity components that could be measured independently.
0.39 times as large as the approximate theoretical value supplied by Kurucz that was listed in Morton’s (1991) earlier compilation (and does not appear in the most recent listing of 2003). Following our derivation of $f(1317)$, we examined spectra of 48 stars (different from the ones used for the 1317/1741 comparison) that had both the 1317 and 1370 Å lines, so that we could improve upon the previously published $f$-value of the 1370 Å line using our value of $f(1317)$ as a comparison standard. This analysis yielded the result $f(1370) = 0.0588 \pm 0.006$, which is 0.76 times the revised value of Zsargo & Federman (1998) given in Morton’s (2003) compilation of $f$-values (and 0.45 times the value given in his earlier listing in 1991, again based on the theoretical values of Kurucz). Our new result for $f(1370)$ differs from the re-scaled value of Zsargo & Federman (1998) by less than their declared uncertainty of 30%. The transition probabilities listed by Fritzsch et al. (2000, from their length calculations using experimentally determined energies), $A_{21}(1317) = 1.95 \times 10^8$ s$^{-1}$ and $A_{21}(1370) = 3.55 \times 10^9$ s$^{-1}$, are equivalent to $f(1317) = 0.0676$ and $f(1370) = 0.0666$, which are respectively only 18% and 13% higher than our determinations.

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Note added in proof.—After our article was accepted for publication, we learned about another determination of the $f$-value of the transition at 1317 Å by M. Dessauges-Zavadsky et al. (A&A, in press [2005]; astro-ph/0511031). The value that they derived (0.057 ± 0.006) is exactly the same as ours, but their quoted uncertainty reflects only the dispersion of their outcomes for several determinations and does not include the uncertainties of the $f$-values of the comparison lines at other wavelengths.