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The astrophysical importance of resonance lines

ABSTRACT

This paper outlines the astrophysical situations in which absorption lines from ground states dominate spectra, the instruments expected to be available to study these spectra, and the gaps in the atomic data where new laboratory or theoretical studies would be very useful.

INTRODUCTION

There are several astrophysical situations where absorptions from the ground states of atoms, i.e. resonance lines, dominate the spectra. In gaseous regions where both the particle and radiation density are low, almost all the atoms will be in their ground states, or at most excited by a few hundredths of an electron volt if a low lying fine-structure level is present. The absorption spectra from such regions thus consist of only resonance lines. With the exception of a few transitions of Na I, K I, Ca I, Ca II, Ti II and Fe I, all these lines occur at wavelengths shortward of the atmospheric cutoff at 3000 Å.

The most familiar example of such a low density region is the interstellar medium, which produces resonance lines in absorption against stars shining through it. The quasi-stellar objects (QSOs) typically have absorption lines, which in many ways resemble ultraviolet interstellar spectra redshifted to visible wavelengths. Thus the QSO lines usually are attributed to low density gas either in intervening galaxies or in clouds in the intergalactic medium.

The ultraviolet spectra of all luminous hot stars show that they have winds which eject material back into the interstellar gas at velocities up to 3500 km s^{-1} (Snow and Morton, 1976). These winds usually are revealed by the ultraviolet resonance transitions of Mg II, C IV, Si IV, N V and O VI, which have emission lines near their expected positions and broad absorption lines extending to shorter wavelengths.

Finally, some ten percent of all QSOs have broad absorption lines blueshifted from the emission lines by as much as 35 000 km s^{-1} (Hazard et al, 1984). The shifted lines are attributed to mass flow from the QSO, by analogy with the hot stars.

OBSERVATIONAL OPPORTUNITIES

Table I summarizes the major space facilities, past and future, that will be suitable for observations shortward of the atmospheric cutoff at 3000 Å. Ground-based telescopes also can observe the UV resonance lines in redshifted QSOs, including lines shortward of the Lyman limit.

WAVELENGTH DATA REQUIRED

The available data on resonance lines have increased considerably since the tabulation by Morton and Smith (1973) and the revisions listed by Morton (1978). Morton, York and Jenkins (1989) summarized the latest data on the stronger transitions which are likely to appear in QSO spectra and noted several cases where improvements were necessary. Since then Kaufman and Martin (1989) have added new wavelength measurements of the O VI resonance lines.

However, as indicated in Table 2, many important transitions still lack sufficiently accurate wavelengths. For brevity only the strongest line from the ground level of each multiplet is given. Although we would like wavelengths to 1 part in 10^6 to take full advantage of the Hubble Space Telescope, in many cases 3 or even 10 parts in 10^6 would be useful improvements on existing data.

In addition, any information on hyperfine structure or isotope shifts for resonance lines with separations exceeding 1 part in 10^6 would be useful. Wayte, Wynne-Jones and Blades (1978) detected the Na I hyperfine structure towards α Cygni, demonstrating that there are regions of the interstellar gas where the line-of-sight velocity dispersion is as small as $\sigma = 0.27$ km s^{-1}. When lines are this narrow, isotope effects also may contribute to the line widths. For example, according to the estimates by Clark (1989), C^{12}-C^{13} = 0.015 Å for C II λ1335 and N^{14}-N^{15} = 0.010 Å for N II λ1085.

Table 1. Observational Opportunities

Telescope	Wavelength Range (Å)	Resolution	Date
Space Observatories			
Copernicus	710-3185	$2\text{x}10^4$, $6\text{x}10^3$	1972-1984
International UV Explorer	1150-3200	300, 12000	1978-Now
Hubble Space Telescope	1150-3200	$2\text{x}10^3$, $2\text{x}10^4$, 10^5	1990 MAR
Hopkins UV Telescope	450-1850	500	1990 APR
Extreme UV Explorer	70- 760	260	1991 AUG
Lyman Far UV Explorer	910-1250	$1.5\text{x}10^4$, $3\text{x}10^4$	~1996
(awaiting approval)	400-1600	$4\text{x}10^3$	
	100- 350	130-900	
Ground-Based Observatories			
10 major Telescopes 3 to 5m	>3000	$<3\text{x}10^5$	Now
Redshifted QSOS ($z>4$)	> 600	"	"
Keck Telescope 10m	>3000	10^5	~1992
ESO Very Large Telescope 4x8m	>3000	$3\text{x}10^5$	1995-2000

Table 2. Lines Requiring Better Wavelengths

Ion	Resonance Line Wavelengths (Å)	Year of Latest Publication
A.	Lines Longward of 912 Å	
P II	1532.51, 1301.87, 1152.81, 963.81	1959
S III	1190.21, 1012.50	1929
Cl III	1015.02	1928
Cl IV	973.21	1928
B.	Lines Shortward of 912 Å	
S III	698.73, 681.50, 677.75, 484.19	1929, 1937
S IV	657.34, 551.17	1925
S V	786.48	1932
S VI	248.99	1937
Cl III	572.69, 557.12	1928, 1934
Cl IV	831.43, 607.09, 599.73, 549.22, 534.73	1928, 1934
Cl V	883.13, 681.92, 633.19, 538.03	1928
Cl VI	671.37	1925
Ar III	878.73, 637.28, 529.90, 488.45, 475.71, 467.39	1935
Ar IV	850.60, 452.91, 396.87	1935
Ar V	705.35, 511.89, 458.12, 337.56	1941
Ar VI	754.93, 588.92, 548.91, 457.48, 292.15	1941, 1961
Ar VII	585.75	1941

TRANSITIONS REQUIRING IMPROVED OSCILLATOR STRENGTHS

An accuracy of 10% or 0.04 dex is very desirable, but 25% or 0.10 dex still would be useful. Weak transitions are particularly important because they often do not need any saturation correction in the analysis. The desired weakness usually is a result of significant cancellation in a dipole transition, or an intersystem change in the spin state. In either case, experiments are difficult and theoretical calculations require many terms. Nevertheless, perseverance with both tactics is well worthwhile until theory and experiment agree.

C II

These weak intersystem transitions from 2323 to 2328 Å are preferred over the saturated lines at shorter wavelengths. However, the calculated values of Cowan, Hobbs and York (1982) and Nussbaumer and Storey (1981) have deviations up to 0.5 dex.

N I

Lugger et al (1978) derived f-values for 18 lines of N I from 1161 to 951 Å using the observed strengths of interstellar lines and experimental values for multiplets 1 and 2. Further experiments to check these results are very desirable, particularly the weak intersystem line at 1159.814 Å.

O I

Zeippen, Seaton, and Morton (1977) published theoretical f-values for many O I lines from 1039 to 919 Å. A few experimental determinations would be very useful to check these calculations. Further theoretical and experimental work on the weak intersystem line at 1355.598 Å should improve our confidence in its use.

Mg II

The determination of the interstellar abundance of this important ion depends on the weak dipole doublet at 1240.395 and 1239.925 Å. At present the best oscillator strength is the theoretical value by Hibbert et al (1983); it is smaller than an earlier calculation of Black, Weisheit and Laviana (1972) by 0.56 dex. An experimental check here is most desirable.

Si II

Recent calculations by Luo, Pradhan and Shull (1989) agree reasonably well with those of Dufton et al (1983) except for the weak dipole transition at 1808.013 Å. Both calculations also give acceptable agreement with the oscillator strengths of λλ1304, 1260, 1193, and 1190 adopted by Morton, York and Jenkins (1989) from lifetime measurements. However, the observed interstellar strength of λ1526 seems systematically too large for the calculated f. Experimental determinations for λλ1526, 1020, 989 and especially 1808 are needed and would provide a reliable curve of growth which could be used for other ions.

Ti III

Measurement of this ion is necessary to determine the titanium abundance in regions where the hydrogen is ionized. Martin, Fuhr, and Wiese (1988) adopted the theoretical value of Kurucz and Peytremann (1975) for λ1291.624, but the accuracy is low.

Cr II

The column density of Cr II relative to Zn II is a useful indicator of condensation on to grains. The lines at 2065.501, 2061.575 and 2055.596 are present in some stellar and QSO spectra. Currently the best oscillator strengths are from the calculations of Kurucz and Peytremann (1975).

Fe II

Like Si II, this ion has many lines accessible to IUE and the Space Telescope, so that the complete curve of growth should be derivable, but the atomic data are not yet reliable enough. Measurements by Moity (1983) and Kroll and Kock (1987) have confirmed the f-values that Morton and Smith (1973) derived from the lifetimes of Assoussa and Smith (1972). However, the careful calculations of Nussbaumer, Pettini and Storey (1981) are larger by amounts ranging from 0.025 to 0.17 dex. Consequently the best f-values at present for the shorter wavelength lines probably are those which Shull, Van Steenberg and Seab (1983) determined from interstellar lines. More laboratory measurements are needed.

Fe III

The iron abundance in H II regions depends on this ion. At present the only oscillator strengths for the lines at 1122.526, and several multiplets shortward of 912 Å are the calculations of Kurucz and Peytremann (1975).

Ni II

Several resonance lines between 1752 and 1308 Å have been seen in stars or QSOs, but the only source of f-values is Kurucz and Peytremann (1975).

Finally, since many experimental and theoretical results on transition probabilities are transformed from multiplets to individual lines under the assumption of LS coupling, it is important to watch for evidence for deviations. Goldbach and Nollez (1987) have presented experimental evidence for deviations in some C I multiplets.

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