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IRON BOLTZMANN FACTOR LIDAR: PROPOSED NEW REMOTE SENSING TECHNIQUE FOR MESOSPHERIC TEMPERATURE

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ABSTRACT

We describe a new lidar technique for upper atmospheric temperature measurement. The proposed lidar exploits the Fe layer in the 80 - 100 km altitude region. Absolute temperatures are inferred by the Maxwell-Boltzmann relationship from the ratio of lidar returns from mesospheric Fe atoms at 372 nm and 374 nm corresponding to the ground-state resonance line and a thermally-populated resonance line, respectively. The wavelengths of the new lidar are favorable for capturing Rayleigh signals from the middle atmosphere. A simulation indicates that a complete temperature profile from 30 - 100 km can be acquired with the proposed lidar by monitoring simultaneously the Rayleigh signals and the Fe fluorescence returns excited by the same transmitter pulse.

SUMMARY

Knowledge of the temperature and density in the upper atmosphere is important for the understanding of a wide range of geophysical phenomenon such as air glow, mesospheric temperature inversions, gravity wave breaking, and reentry effects; and for discerning trends in global climate changes. The standard meteorological techniques currently employed in the United States for mesospheric temperature measurements include datasonde rockets for measurements between 20 and 65 km and the passive sphere for altitudes between 30 and 90 km. Recently, nadir-viewing satellites with onboard radiometric sensors have contributed to the acquisition of temperature profiles. However, these methods currently lack the accuracy and spatial resolution required for many of the above applications.

In this paper, we describe a new lidar technique for temperature sensing based upon optical interactions with free Fe atoms in the mesosphere. The technique can be best understood with the aid of Figure 1. Displayed in the figure is a partial energy level diagram of atomic Fe. The ground a^5D level is split into fine structure components. The separation between the lowest energy members of the quintet is 416 cm^{-1}. Both levels are optically coupled to the z^5F^o level centered at 3.375 eV. The $z^5F^o{}_5$ --- a^5D_4 transition corresponds to 372 nm and is considered the primary resonance line. The $z^5F^o{}_4$ --- a^5D_3 transition occurs at 374 nm and is another resonance line. Both transitions possess moderate oscillator strengths, namely, 0.04, and upon excitation decay by emission of resonance radiation.

Iron atoms in the mesosphere may be considered in thermal equilibrium with their surroundings. Hence, the population in the ground level J" = 3 component is related to the population in the J" = 4 component by the Maxwell-Boltzmann relationship; namely,

$$n\,(J''=3) / n\,(J''=4) = (g_2 / g_1)\ \exp(-\Delta E / k\,T), \tag{1}$$

where n is the level population, $g_{2,1}$ are the degeneracy factors of the J = 3 and J = 4 levels, respectively, Δ E is the energy separation of the two levels, k is Boltzmann's constant, and T is temperature.

The right hand side of Eq. (1) is the well-known Boltzmann factor. From Eq. (1) we note that the population ratio is a function of temperature. Thus, the proposed new method for monitoring upper atmospheric temperature involves the transmission of laser pulses alternately at 372 nm and 374 nm and monitoring the corresponding fluorescence returns. Absolute temperature is inferred from the ratio of the return signals via the Boltzmann factor. Hence, we call the new remote sensing technique the Fe Boltzmann factor lidar or Fe temperature lidar.

Let us now derive the relationship between lidar signals and temperature. The lidar equation for zenith-viewing fluorescence lidar can be written as

$$S = (E / h\nu)\, n\, \sigma\, L\, (A_r / 4\pi z^2)\ T_a^2\, T_o\, \eta, \tag{2}$$

where S is the photoelectronic counts, E is the transmitter pulse energy,
hυ is the photon energy, n is the density of the fluorescence species,
σ is the absorption cross-section, L is sample cell length or spatial resolution,
A_r is the receiver area, z is the altitude,
T_a is the one-way atmospheric transmission, T_o is the transmission through the receiver,
η is the photomultiplier (PMT) quantum efficiency.

Because of the reduced molecular density in the metallic layer, contributions to atomic line broadening from collisions are much less than the spectral spread due to the thermal motion of the radiating atoms. Hence, we assume for computational purposes purely Doppler-broadened lineshapes in the metallic layer. The Doppler-broadened absorption cross-section is related to the Einstein transition probability, A, by

$$\sigma = (2 / \Delta\nu_D)\ \sqrt{\ln 2/\pi}\ (\lambda^2/ 8\pi)\, (g_u / g_l)\, A, \tag{3}$$

where $\Delta\nu_D$ is the Doppler linewidth, λ is the wavelength, and $g_{u,l}$ are the degeneracy factors of the upper and lower levels, respectively.

Substitution of Eqs. (1) and (3) into Eq. (2) yields

$$[\,S\,(374\text{ nm}) / S\,(372\text{ nm})\,] = (\lambda_2\, \sigma_2\, g_2 / \lambda_1\, \sigma_1\, g_1)\ \exp(-\Delta E / k\,T). \tag{4}$$

The spectroscopic parameters for the Fe transitions of interest are as follows: $g_2 = 7$, $g_1 = 9$, A(374 nm) = 0.142 x 10^8/sec, A(372 nm) = 0.163 x 10^8/sec, σ (374 nm) = 8.78 x 10^{-13} cm^2, and σ (372 nm) = 9.45 x 10^{-13} cm^2. The cross-sections were calculated assuming Doppler broadened linewidths at 200 K. Substitution of the above values into Eq. (4) yields

$$[\ S\ (374\ \mathrm{nm})\ /\ S\ (372\ \mathrm{nm})\ ] = 0.73 \exp(-\Delta E / kT). \qquad (5)$$

By substitution of Eq. (3) into Eq. (4), it is readily seen that the ratio of signals depends upon ΔE, k, and the ratio of: wavelengths, degeneracies, and transition probabilities. Hence, the absolute accuracy of temperature measurement by the new lidar technique depends upon the accuracy to which each of the above factors is known. With the exception of the transition probabilities, all of the parameters are known to within 0.1%. The uncertainties associated with the transition probabilities at 372 and 374 nm are approximately 10%; however, the relative accuracy of the two transition probabilities is less than 0.5%. Therefore, the accuracy of the Fe Boltzmann factor lidar method is better than 1%.

Because the proposed Fe Boltzmann factor lidar monitors signals with high precision from 80 - 100 km, it is natural to contemplate its simultaneous usage as a Rayleigh lidar at lower altitudes. In this manner a complete temperature profile could be acquired throughout the 30 - 100 km altitude range. The simulated performance of the proposed dual-wavelength Fe lidar is shown in Fig. 2. Plotted are the single-shot Fe resonance fluorescence returns at 372 nm and 374 nm and Rayleigh signals for the 30 - 100 km region. A representative Fe density profile was taken from work at UIUC [1]. The maximum Fe density in this profile was 2.1 x 10^4 cm^{-3}. We observe from Fig. 2 that the Rayleigh returns from the lower mesosphere are of comparable magnitude to the Fe signals at the higher altitudes; a result that is independent of system parameters. This finding suggests that a complete temperature profile from 30 - 100 km can be obtained from the analysis of returns from a single lidar operating on the Fe resonance lines.

Another significant advantage of this technique is noted; since Rayleigh and Fe fluorescence signals can be obtained at the same altitude, temperature inferred from the Fe densities can serve as a high end-point absolute calibration for the Rayleigh lidar measurements.

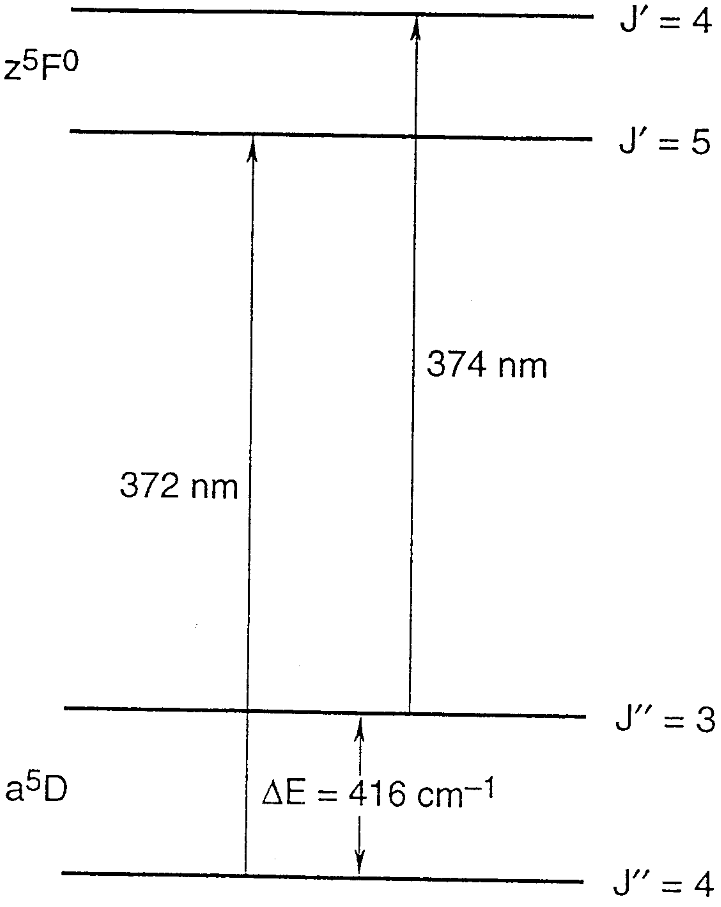
REFERENCE

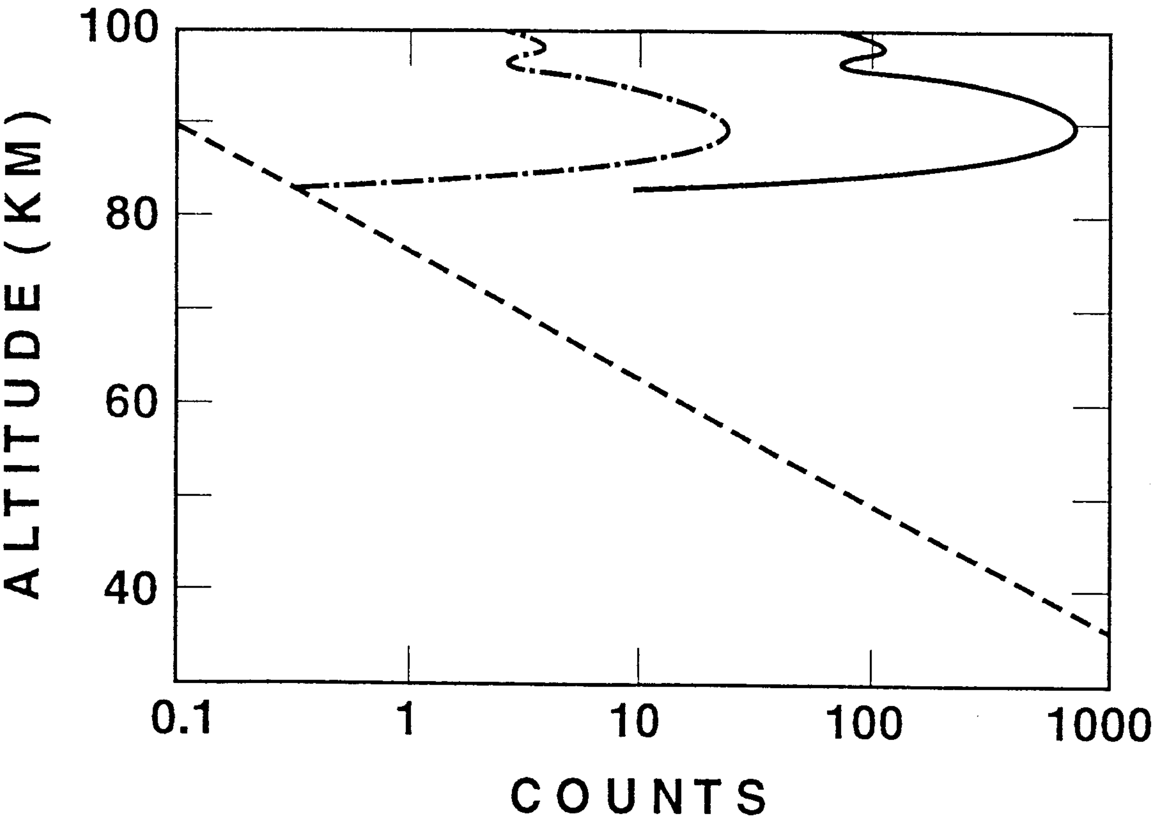
1. T. J. Kane, P. H. Mui, and C. S.Gardner, "Evidence for substantial seasonal variations in the structure of the mesospheric Fe layer," Geophys. Res. Lett. **19**, 405-408(1992).

FIGURE CAPTIONS

Figure 1. Partial energy level diagram for atomic Fe.

Figure 2. Lidar simulation of the middle atmospheric signals expected at the primary Fe resonance line (solid curve), the temperature-sensitive Fe resonance line (broken curve) and Rayleigh lidar (dashed curve).


J′ = 4
z^5F^0
J′ = 5
374 nm
372 nm
J″ = 3
a^5D
$\Delta E = 416\ cm^{-1}$
J″ = 4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80
60
40
ALTITUDE (KM)
0.1
1
10
100
1000
COUNTS