ATMOSPHERIC EMISSION IN THE 20-μm WINDOW FROM MAUNA KEA

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The emission spectrum within the 20-μm window of the atmosphere above Mauna Kea has been measured to a resolution of 0.01 cm⁻¹ with a Michelson interferometer and compared to a single-layer synthetic spectrum in order to test the feasibility of observing fine-structure emission lines from astronomical sources from this site. It is demonstrated that the observed spectrum can be very closely simulated by the inclusion of CO₂, H₂O, and N₂O in the synthetic spectrum, a situation which is presumed to hold for other high, dry observing sites. The present data indicate that large telescopes equipped with high-resolution spectrometers can still be used to advantage in the observation of selected fine-structure lines against the background emission from these sites, particularly when careful background subtraction techniques are used.

Key words: midinfrared—atmospheric emission—interferometry—fine structure lines

I. Introduction

Measurements of collisionally excited fine-structure emission lines provide an important tool for the evaluation of the physical processes occurring in a variety of astronomical sources. From these measurements it is possible to determine electron density, ionic abundance, ionization structure, and the dynamics of the emitting region (Lacy 1981; Watson and Storey 1980). The interpretation of infrared emission lines is often easier than that of their optical counterparts. First, since the excitation temperatures of the fine structure levels are small compared to the ambient plasma temperature, the derived physical parameters are virtually independent of the assumed electron temperature. Second, infrared lines are relatively unaffected by extinction due to interstellar material and their measurement is therefore particularly well suited to the study of sources which are heavily obscured at visible wavelengths.

One of the major problems in the study of infrared emission lines is that most of them occur in regions of poor atmospheric transmission, and for this reason the majority of observations to date have been obtained with aircraft or balloon-borne instrumentation. Airborne observations are limited to relatively small telescope diameter and short observing runs, are made in a hostile environment, and are relatively expensive. In contrast, ground-based measurements of selected lines using large telescopes from the best observing sites offer an attractive alternative if atmospheric infrared windows are sufficiently transparent.

The present paper seeks to test the feasibility of such ground-based astronomical observations in the 20-μm window from an excellent infrared site at Mauna Kea, Hawaii, by carrying out a detailed comparison of the observed high-resolution (0.01 cm⁻¹) atmospheric emission spectrum in this wavelength range with an equivalent synthetic spectrum.

Of the astrophysically significant fine-structure lines in this wavelength range, one of the strongest is the 3P₂⁻⁻→⁻⁻⁻⁻₃P₁ transition of S III (S⁺⁺⁺⁺) at 18.71 μm. In view of the potential confusion in the discussion of the detectability of this line in recent literature, it is instructive to consider this situation further. This line was first detected by Baluteau et al. (1976) using a Michelson interferometer on the 0.91-m telescope of the Kuiper Airborne Observatory. Subsequently, Greenberg, Dyal, and Geballe (1977) used a Fabry-Perot/cooled-grating spectrometer combination in sky-chopping mode on the University of Hawaii 2.2-m telescope on Mauna Kea to detect S III emission from three galactic nebulae. From these results Greenberg et al. concluded that the proximity of the S III line to an atmospheric H₂O line would make airborne observations desirable for future work. All subsequent measurements of this line have used airborne instrumentation (Moorwood et al. 1978; McCarthy, Forrest, and Houck 1979; Moorwood et al. 1980).

One further point which perhaps led to the above conclusion on the necessity for airborne observations is the fact that the H₂O line position is wrongly listed at 534.32 cm⁻¹ in the 1979 version of the 1973 AFCRL at-
mospheric-line parameter compilation (McClatchey et al. 1973), although later H$_2$O line positions listed by Flaud, Camy-Peyret, and Maillard (1976) are in closer agreement to experimentally observed values. Thus, a theoretical prediction of the feasibility of ground-based observations of the S III line using this earlier data base would have been misleading. The separation of the S III line from the H$_2$O line, while significantly below the resolution of the instrument of Greenberg et al. in their earlier work, is well within the capabilities of a modern Fourier transform spectrometer. This has provided the initial impetus for the present high-resolution study of atmospheric emission in the 20-micron window from Mauna Kea.

II. Observations

The present observations were made in August 1981 at the f/35 Cassegrain focus of the 3-m IRTF on Mauna Kea using the high-resolution Fourier transform spectrometer developed by the infrared astronomy group at European Space Agency (Anderegg et al. 1980). The characteristics of this instrument are shown in Table I.

This interferometer was specifically designed for an f/8 Cassegrain beam and transfer optics were normally utilized to adapt this instrument to other telescope systems. A mechanical problem with the interface between telescope and interferometer resulted in an optical mismatch for this initial observing run, but the data provided excellent observations of atmospheric emission spectra for use in the present evaluation. These spectra were produced from the measured interferograms by phase correction and Fourier transformation using the technique of Boucher and Naylor (1981), while internal calibration was provided by blackbody observations at two temperatures.

A curve-of-growth technique (Naylor, Clark, and Borreiko 1981) was used to determine column abundances for the three major contributors to the emission, H$_2$O, CO$_2$, N$_2$O, for comparison with the theoretical synthesis. Emission lines in this wavelength range fall into two asymptotic regions, the weak- and strong-line approximations (Goody 1964), for which the equivalent width $A$ (cm$^{-1}$) of an emission line is given by $A = S u$ in the weak regime and by $A = 2 S (a_L)^{1/2}$ in the strong regime, where $S(T)$ is the temperature-dependent line strength (cm$^{-1}$/molecule cm$^{-2}$), $a_L(p,T)$ is the pressure- and temperature-dependent half-width (cm$^{-1}$) and $u$ is the column abundance (molecule cm$^{-2}$). $S$ and $a_L$ are tabulated in the AFCRL atmospheric-line parameter compilation (McClatchey et al. 1973) at a standard pressure and temperature, $T_0$, $p_0$. If the height distribution of each constituent is roughly known such that emission due to each constituent can be assumed to occur within a single layer, values of mean pressure $p_m$ and temperature $T_m$ can be assigned according to the Curtis-Godson approximation (Goody 1964). The column abundance $u$ can be determined from the measured values of $A$ with the above information on $S(T_0)$, $a_L(p_0,T_0)$, and the chosen values of $p_m$ and $T_m$ which are tabulated in Table III. Since the majority of H$_2$O and CO$_2$ lines occur in the strong regime, the column abundances, $u$, for these constituents can be determined from graphs of $A$ vs. $S(T) \times a_L(p,T)^{1/2}$ with $u = m^2/4$, where $m$ is the slope of the graph. The majority of the N$_2$O lines in this wavelength range occur in the weak regime. The column abundance is then determined from the slope of $A$ vs. $S(T)$. Curves of growth for each of the three constituents are shown in Figure 1. Only unblended lines were used in the analysis. The linear least-squares fit to the data for each con-

![Figure 1](image-url)

**TABLE I**

<table>
<thead>
<tr>
<th>Instrumental Characteristics</th>
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<td>Spectral range</td>
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<td>Calibration</td>
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stinent is shown in the graphs of Figure 1, while column abundances determined from the slopes of these lines are tabulated in Table II. The last column gives the vertical column abundance after taking into account an air-mass factor of 1.24.

III. Theoretical Synthetic Spectra

The synthetic spectra generated for comparison with the observational data were based upon the AFCRL atmospheric-line parameter compilation of McClatchey et al. (1973). A single layer approximation to the atmosphere was considered sufficient since the primary purpose of the synthetic spectrum was line identification, rather than a detailed line-by-line matching to the observations. The constituent amounts used in the synthesis were initially chosen to be those used in the Kyle-Goldman Atlas of 1975. Although there is good agreement between the amounts of CO$_2$ and N$_2$O used in the Atlas and those determined experimentally, the measured amount of H$_2$O was significantly below the value used in the Atlas, and so the H$_2$O column abundance used in the synthesis was reduced accordingly.

Table III lists the parameters used in the generation of the synthetic spectrum. The values of the mean temperature and pressure for H$_2$O differ from those of the other constituents to account for the greater concentration of this constituent in the lower atmosphere. The intrinsic (infinite-resolution) synthetic spectra were convolved with an instrument function of the form $(\sin x/x)^2$ with a resolution of 0.01 cm$^{-1}$ to match the spectral resolution and instrument function of the apodized interferometer output. Lines were assumed to have purely Lorentz wings, but with the contribution from a particular line ignored beyond 5 cm$^{-1}$ from its line center. This results in small but abrupt terminations in predicted emission from several of the H$_2$O lines in the present synthesis, which is almost undetectable in the resulting spectrum.

IV. Results

The comparison between the atmospheric emission spectrum from Mauna Kea and the single-layer synthetic model using the three major contributors to emission in the spectral range 455–635 cm$^{-1}$ is shown in atlas form in Figure 2. The lower trace shows the observed spectrum. The upper traces show the theoretical emission expected from each of the three contributing constituents, plotted linearly from zero to complete (equivalent blackbody) emission for H$_2$O and CO$_2$, and on the same scale for N$_2$O.

V. Conclusions

The results in Figure 2 for the emission spectrum in the 20-micron window show that all major detectable features in the observed spectrum are accounted for by the three constituents H$_2$O, CO$_2$, and N$_2$O. The detailed comparison of a combined synthetic spectrum with the experimental data, while possible, was not thought useful in the present context in view of the expressed aim of line identification in the observed spectrum. Night-by-night variability of constituent concentrations, particularly of H$_2$O, would make such a comparison of limited relevance. A complete line-by-line comparison of observed spectra with a multilayer synthesis, using constituent amounts derived from curve-of-growth analysis can be expected to show excellent agreement, but searches for lines in astronomical sources would utilize an off-source background comparison spectrum rather than a synthetic spectrum in general. The extremely low amount of H$_2$O measured above Mauna Kea (0.34 ± 0.03 mm precipitable H$_2$O) during this particular observing run certainly reinforces the claim that Mauna Kea is an excellent infrared observing site.

As an initial test of the feasibility of fine-structure line measurement against this background, a simulated $S$ line from a bright astronomical source has been superimposed upon the measured spectrum in Figure 3. With careful attention to spectral matching and due allowance for varying air-mass, background subtraction should permit the measurement and mapping of the intensity of this line from much weaker sources than that of the simulated line in Figure 3.

It is anticipated that this atlas of atmospheric emission in Figure 2 will be a useful guide in the design of observing programs for other astrophysically significant lines in this spectral region. The accuracy of fit of this simple spectrum synthesis indicates that the present approach might be used with equal facility for other sites and atmospheric conditions.

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Fig. 2—The observed emission spectrum of the atmosphere above Mauna Kea between 455 and 515 cm$^{-1}$, compared to the single-layer synthetic spectra of H$_2$O, CO$_2$, and N$_2$O, using the parameters listed in Table III.
Fig. 2—The observed emission spectrum of the atmosphere above Mauna Kea between 515 and 575 cm$^{-1}$, compared to the single-layer synthetic spectra of H$_2$O, CO$_2$, and N$_2$O, using the parameters listed in Table III.
Fig. 2—The observed emission spectrum of the atmosphere above Mauna Kea between 575 and 635 cm\(^{-1}\), compared to the single-layer synthetic spectra of H\(_2\)O, CO\(_2\), and N\(_2\)O, using the parameters listed in Table III.
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