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The advances in diagnostic techniques and basic studies concerning the Earth's atmosphere made under the auspices of AFOSR are described in this report. Highlights of the investigations are the following:

a) the development and exploitation of a new field of atmospheric investigations using molecular species as passive tracers of the motion and temperature of the mesosphere. This new development is the first method devised to measure *simultaneously* the winds and temperatures of this poorly understood region of the atmosphere.

b) The attainment of a working, stable, rugged, monolithic electrooptic solid-state cavity whose spacing can be arbitrarily and precisely manipulated by applied electric field. This breakthrough in interference optics provides the opportunity to use small, high-luminosity, high-resolution Fabry-Perot spectrometers which require no adjustments for their operation. Such instruments will make it possible to make unmanned observations of unique geophysical events at isolated stations.

c) Because of the proven robustness of our AFOSR-supported developments in teleautonomous operation of instrumentation, we have installed and are conducting two high-resolution diagnostic ground-based atmospheric experiments in the Southern Hemisphere at South Pole (Antarctica) and New Zealand. Neither of these experiments is accessible to the investigators more than twice yearly; they have been successfully operated for six instrument-years.

The data obtained from the field experiments have increased the basic understanding of upper atmosphere dynamics and circulation in the two polar regions. The results of these investigations are published in the open literature, and have contributed to current global semi-empirical models of these regions of the atmosphere. Some of the data were specifically obtained in direct support of Air Force needs at Poker Flat Range. This grant has partially supported four graduate students in their research investigations leading to advanced degrees.

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University of Washington

Final Report

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Introduction

The status of the understanding of the dynamics and thermodynamics of the upper atmosphere at the time grant AFOSR-89-316 started was presented in an AFOSR-supported review by Hernandez and Killeen (1988). There it was noted that significant exploratory work was needed in the topic of mesosphere-thermosphere coupling as there were little, if any, quantitative data to test the hypotheses that wave and tidal forcing processes of mesospheric origin can have significant effects on the thermosphere.

The lower thermosphere and mesosphere are characteristically poorly understood, owing to the paucity of suitable optical measurements of these regions and because of the difficulty of maintaining satellite orbits in the appropriate altitudes for *in situ* sensing.

At the time, there existed only a pilot test of a proven method to measure simultaneously both the motion and temperature of the atmosphere in that region by ground-based sensing methods using naturally-occurring molecular emissions (Hernandez and Smith, 1984). This AFOSR-supported development had shown both the capabilities of the method and the improvements needed to make this a viable approach.

The new mesospheric and lower thermospheric investigations and their extensions quickly proved tractable because of the available (AFOSR-supported) state-of-the-art spectrometer already in operation at Poker Flat, Alaska, the expertise in atmospheric investigations at both Universities of Washington and Alaska, the in-progress work in teleautonomous operation of equipment, and our ongoing theoretical and experimental development of high-resolution optical devices. In addition, some tests under progress (Romick et al., 1987) had shown that the right choice of molecular emissions would make it possible to study the mesosphere in the polar regions without contamination of auroral emission processes. This new field of optical atmospheric investigations was a compelling reason to continue the work at Poker Flat.

Investigations

The investigations performed under AFOSR-89-0316 consist of a close interweave of diagnostics and measurements of the upper atmosphere, supported by a research program in optical and spectroscopic devices, techniques, and measurement methods. The

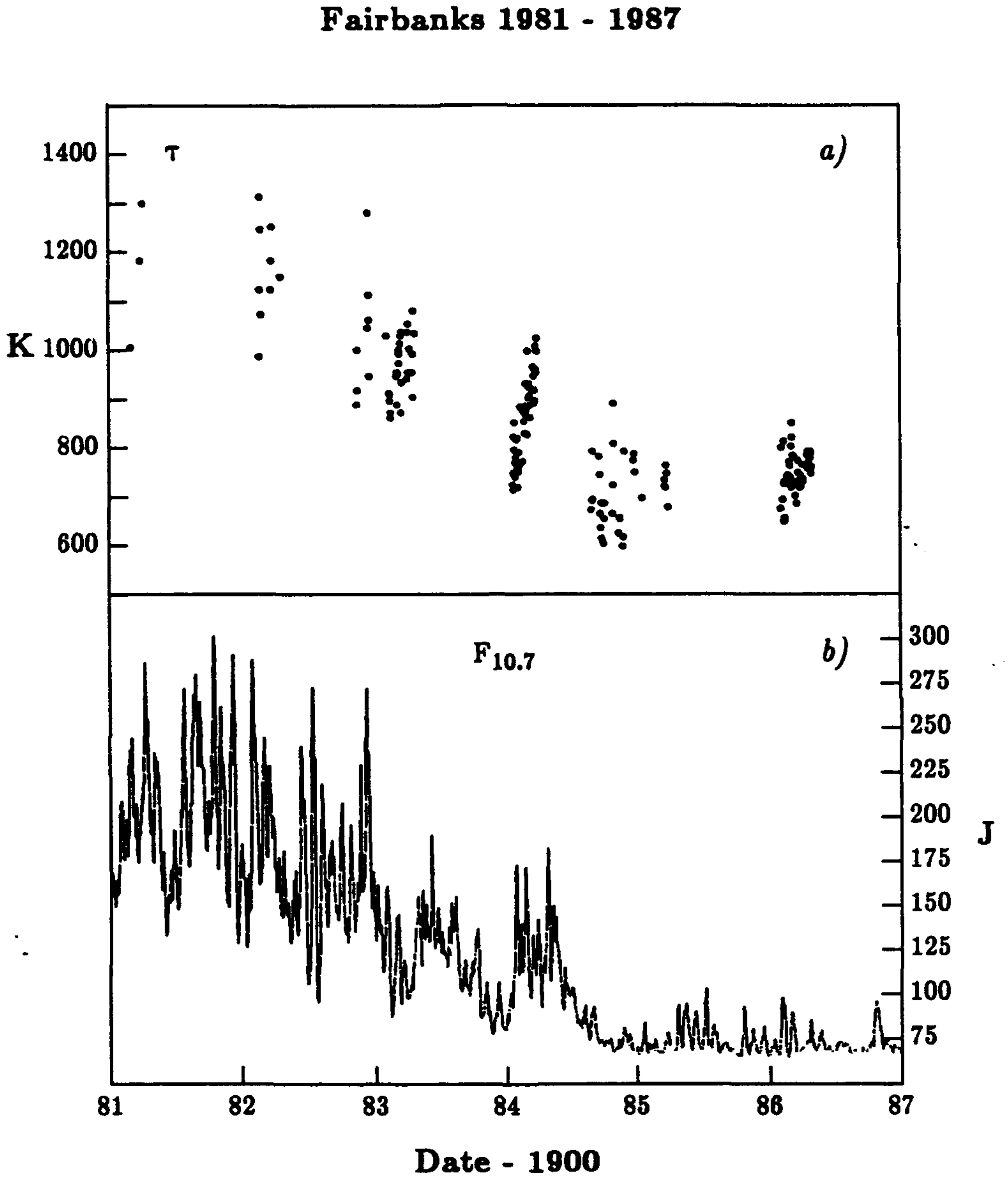

Fig. 1. *a)* Thermospheric temperatures at the polar regions (Poker Flat, Alaska) and *b)* solar activity expressed by the solar radio flux $F_{10.7}$. Note the temperature decrease with decreasing solar activity.

requirements of the field program have spawned new devices suited for the measurements (such as the compensated Double Etalon Modulator), while the developments in optical investigations have generated new field programs (such as the investigations of mesospheric motions and temperatures using molecular species as tracers).

These interactive investigations are not easily separable, but we can arbitrarily treat them independently as long as one remembers there exist no sharp boundaries between them. For convenience, we will call them field and laboratory studies.

Field studies

The investigations on the upper thermosphere, begun under earlier AFOSR support, have been continued in order to improve understanding of the global dynamic behavior of that region of the atmosphere. Upgrading the instrument with broad-band reflecting coatings and making its operation teleautonomous have enabled the collection of diagnostic measurements simultaneously in conjunction with other (globally) spaced stations. Figure 1 illustrates the behavior of the upper thermosphere with (decreasing) solar activity. Some of these results have been published (Smith et al., 1989) showing experimentally the large-scale effects of the Northern Hemisphere magnetospheric convection pattern on the Earth's upper atmosphere. This shown in Figure 2. Further, the high-latitude data obtained during the tenure of this experiment have been used in developing a global semi-empirical model of the upper thermosphere motions (Hedin et al., 1991). The local effects of the aurora on the atmosphere have also been studied (Sica et al., 1992).

In keeping with the global-scale study of the upper thermosphere in the polar regions, the proven robustness of our teleautonomous system in Alaska has made it possible to two other instruments in the Southern Hemisphere midlatitude (Tekapo, New Zealand) and polar regions (South Pole, Antarctica). The latter instrument is inaccessible to the experimenters for nearly 9 months during the year, and during this time it is overseen by personnel with very limited training. These Alaska and Antarctic stations in opposite hemispheres have made it possible to study the effects of the interplanetary magnetic field on the motions of the atmosphere at two widely geomagnetically separated stations (Sica et al., 1989; Hernandez et al., 1991), illustrated in Figures 3 and 4, as well as to study and interpret the behavior of the neutral motions and temperatures with the aid of empirical modeling (Hernandez et al., 1990; Hernandez and Roble, 1992).

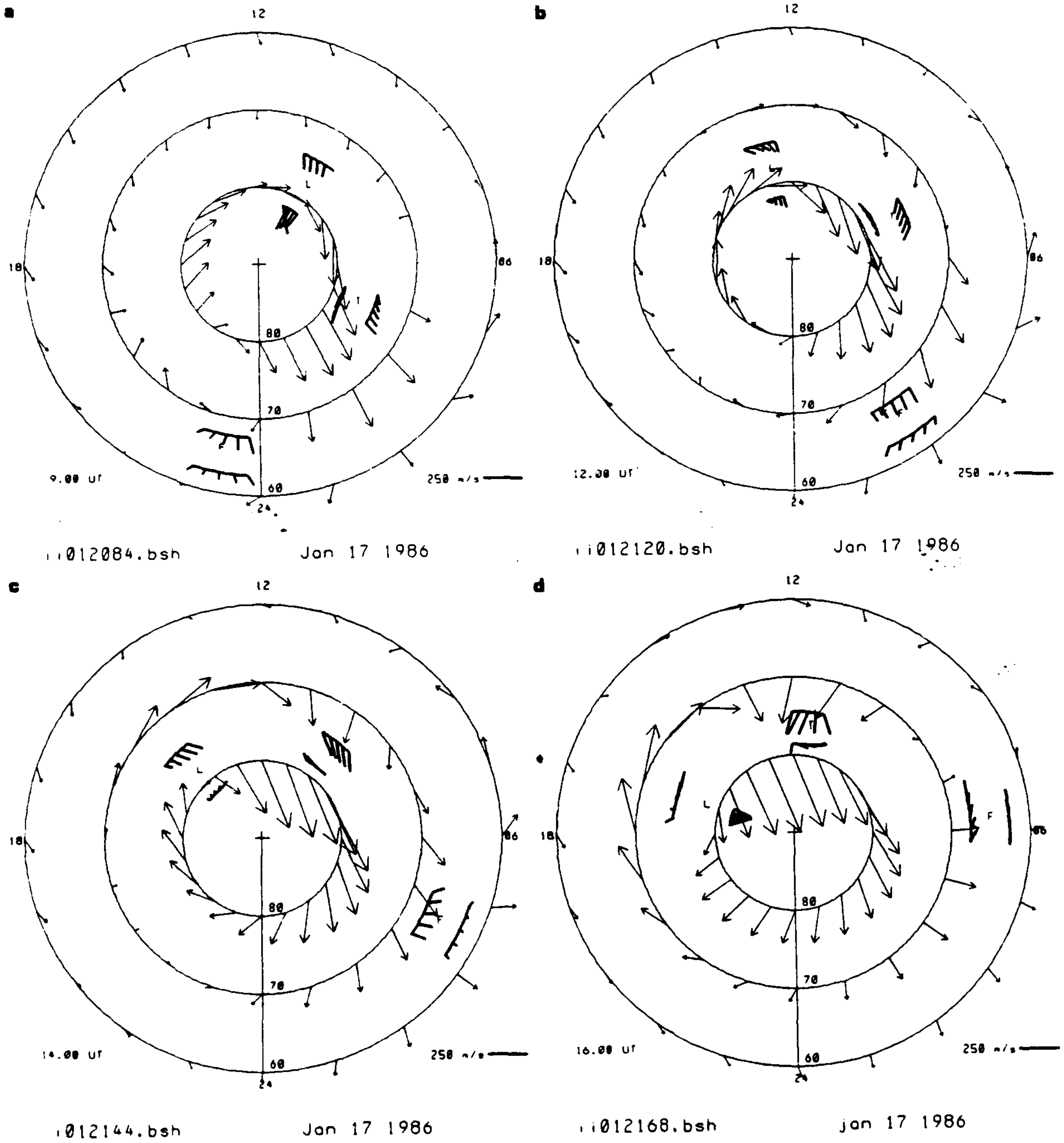

Fig. 2. Polar plots of the neutral wind measured from Thule (T), Svalbard (L), and Fairbanks (F). Panels a-d cover Universal Times 0900, 1200, 1400 and 1600. For comparison, a simulation is shown as backdrop with arrows. From Smith et al., 1989.

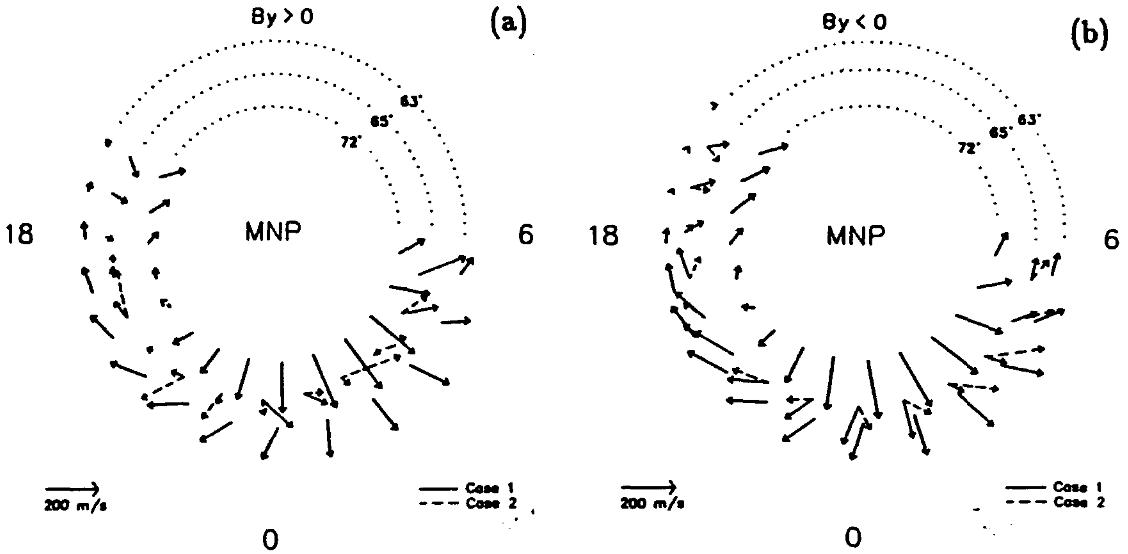

Fig. 3. Vector dial plots illustrating the effects of IMF on the upper atmosphere circulation at Fairbanks, AK. (a) for By positive and (b) for By negative. From Sica et al., 1989.

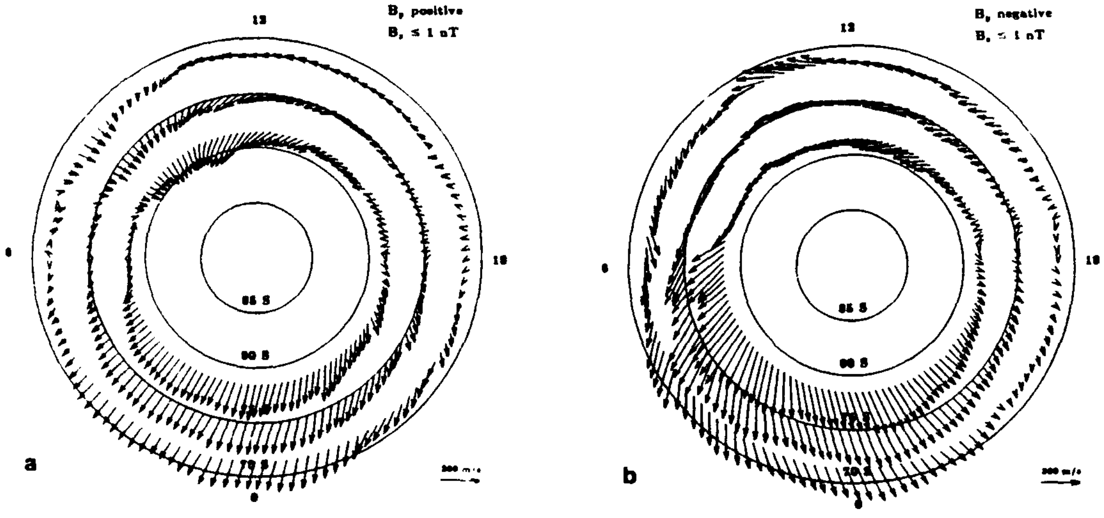

Fig. 4. Vector dial plots illustrating the effects of IMF on the upper atmosphere circulation at South Pole, Antarctica. (a) for By positive and (b) for By negative. From Hernandes et al., 1989.

Some of our investigations in Alaska have included support of Air Force experiments at Poker Flat Range. Results, obtained while in support of the SPIRIT 2 experiment, have shown the simultaneous presence of large neutral winds in the lower and upper thermosphere near the poleward edge of the aurorae (Price et al., 1992). The results are shown in Figure 5. This new topic is being actively investigated.

The highlight of our field experiments has been the opening of a new field of atmospheric investigation by the use of molecular species as tracers of the motion and temperature of the upper atmosphere. The first pilot study on the feasibility of this new experiment was done under AFOSR support (Hernandez and Smith, 1984). This present experiment required a radical departure in the instrumental configuration, mainly a broad-band etalon coating to operate in the near-infrared region of the spectrum. This choice was necessary, since the best molecular emission to observe for these measurements is the $P_1(2)$ line of the 6-2 vibrational level of the OH molecule. A further challenge was presented because this emission line is λ-doubled by electronic orbital and nuclear rotational angular momentum coupling of the molecule, which means that these double lines are very close together and unlikely to be selectively separated.

The results from this study have been gratifying, since we have solved the problem of data reduction of the measurements into motions and temperatures using the double-line spectrum (Hernandez et al., 1992a), and further have made a critical study of the methodology involved in the reduction of such data, a problem heretofore not solved (Conner et al., 1992). Figure 6 shows the mesospheric winds derived from Poker Flat with this new technique. The interferometric spectrometer at Poker Flat was damaged by roof leakage late spring 1989, resulting in an uncomplicated delay of continued measurements until late in the 1990 season.

In the meantime, the same measurements were also being made in the Southern Hemisphere at high-latitude (South Pole, 90°S), with the methodology we learned from the AFOSR-supported research at Poker Flat. From the information gathered there, we have succeeded in publishing the first ever *simultaneous* measurements of the motions and temperatures from the mesosphere (Hernandez et al., 1992a,b), shown in Figure 7. Further study of the polar data showed that only wavenumber one oscillations in the winds were being observed, while temperature oscillations at the same periodicity were statistically not significant. This is illustrated in Figure 8. A close examination of the

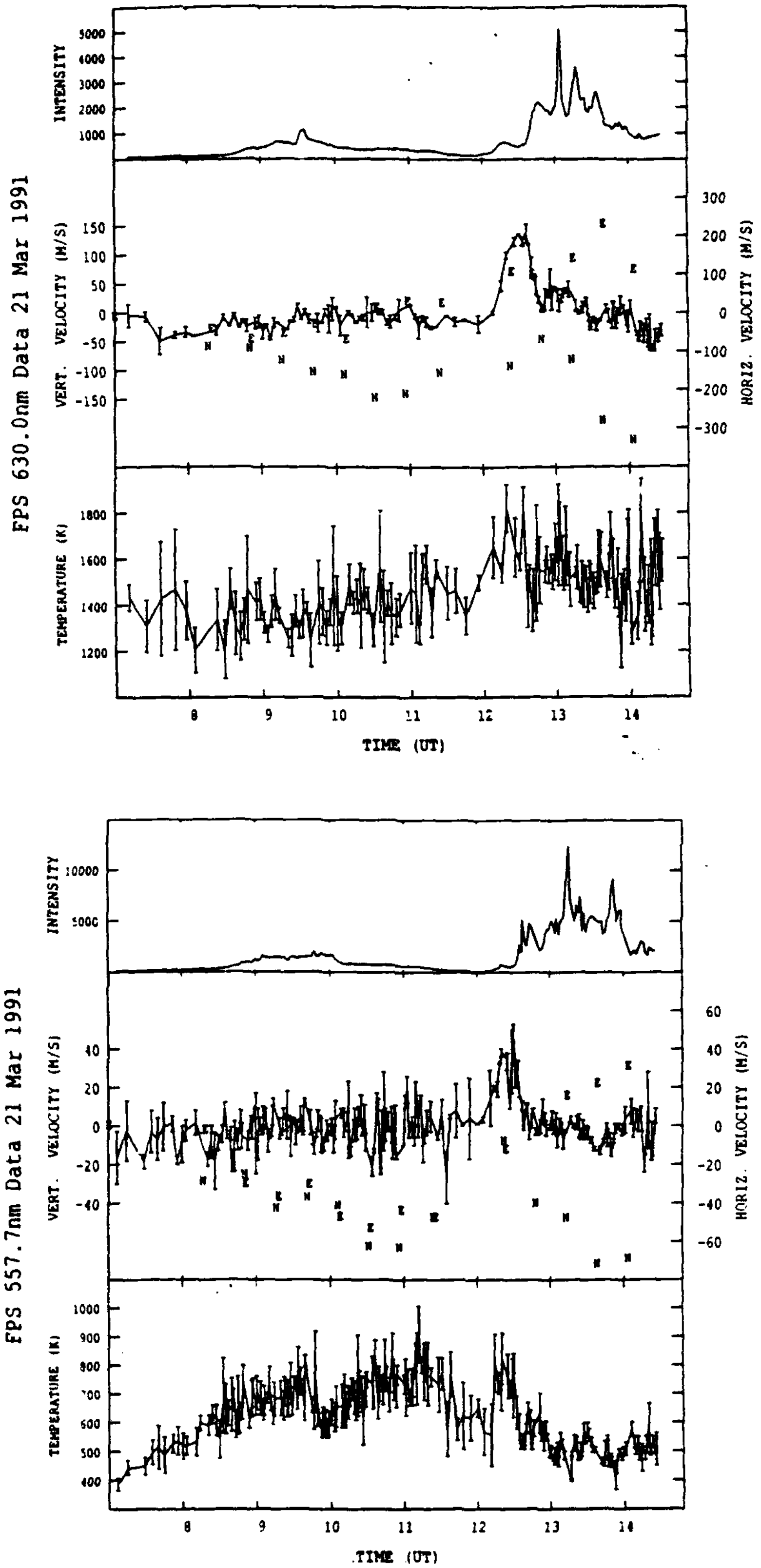

Fig. 5. Vertical winds in the *lower* and *upper thermosphere* during an auroral event. Note the change in vertical velocity previous to the aurora coming into the field of view. From Price et al., 1992.

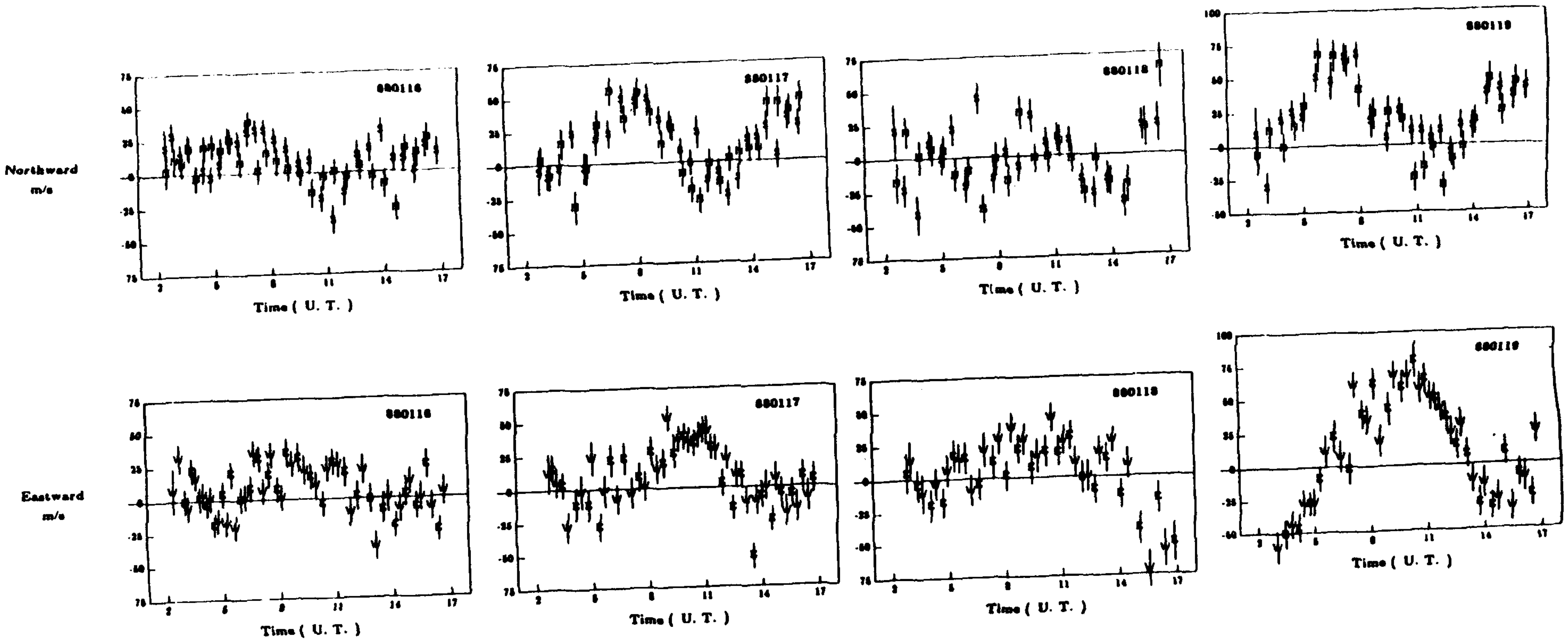

Fig. 6. Measurements of mesospheric winds using molecular emissions as tracers. Measurements from Poker Flat, AK. The last panel has been displaced upwards to keep the scales equal.

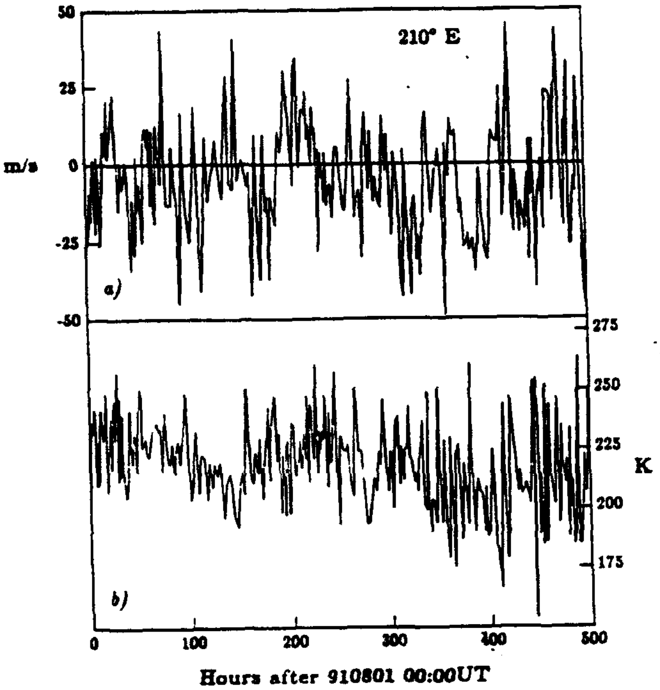

Fig. 7. Simultaneous measurements of wind and temperature in the mesosphere, made at South Pole, Antarctica. *(a)* wind and *(b)* temperature. The data series covers the first 500 hours of measurement for the period August 1, 1991 through August 25, 1991. From Hernandes et al., 1992b.

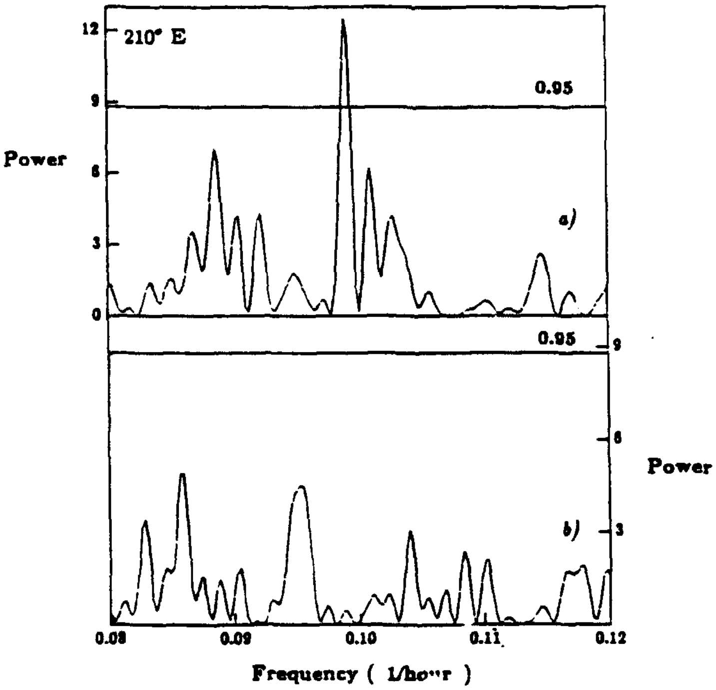

Fig. 8. Modified power spectra for the South Pole data of Fig. 7 for the *(a)* neutral motions and *(b)* kinetic temperatures. Null hypothesis 95% significance levels are indicated. From Hernandes et al., 1992b.

behavior of waves near the poles shows a fundamental reason for the absence of high wavenumber motions at these locations (Hernandes et al., 1992c). This can be found by expanding the variables of the equations of motion in a power series of sinΘ, where Θ is the colatitude; the leading terms of the equations show the behavior near the poles. If s is the sonal wavenumber, then near the poles the pressure and temperature will vary as $(\sin\Theta)^s$, and only for wavenumber zero can they be large; physically, they cannot vary with longitude without being discontinuous at the poles. The horizontal winds are found to vary as $(\sin\Theta)^{s-1}$, and zonal wavenumber one will be observed at the poles. A wind that is continuous and blows across the poles resolves into a wavenumber one as well. This theoretical development, driven by the observations, is of a fundamental nature in the meteorology at high latitudes, as it is independent of height. Our mesospheric observations have brought to light this general global property of the atmosphere to light and indicate the singular importance of a high-latitude station for these measurements.

Laboratory studies

The laboratory investigations under this grant have been a radical departure from earlier studies, as we are involved in new solid-state technology, as applied to optical interference devices. The concept, or goal, has been to attain a rugged and inherently stable optical cavity, whose spacing can be arbitrarily and precisely manipulated. The approach taken has been to make such a cavity from a single-crystal electrooptic material, since the optical cavity's optical thickness can be varied with a longitudinal electric field.

The transformation of this idea into a real device required the procurement of large-size (greater than 3 inches diameter) electrooptic single-crystals with negligible optical flaws and homogeneous index-of-refraction (less than 0.0001 variation) over the full aperture. The two faces of the cavity need to be polished flat to very-high precision (better than 100 billionths of one inch over the aperture), as well as be made parallel to the same precision (in a phase front sense). Finally, each polished face is required to be coated with a semi-transparent multilayer broad-band mirror coating which must preserve the polished surface quality and be a proper match between the crystal's index-of-refraction and the outside world, as well as being electrically conductive. When this investigation began, the above mentioned combination of manufacturing steps had not been attempted before in the scale required by our concept.

Two crystal samples were obtained, polished, coated, and given their first test early 1990. The behavior of the cavity was, at first, erratic in the presence of the electric field, and this was found to be caused by imperfect electrical coupling to the cavity. After this electrical coupling problem was resolved, the cavity operated to expectations, as shown in Figure 9. This proof-of-concept experiment has opened a new vista in spectroscopic instrumentation that depends on the interference of light for its operation.

The significance of this breakthrough is better explained within the context of present-day air gap Fabry-Perot cavities, or etalons. These devices consist of two extremely flat coated surfaces which must be held both parallel and at a fixed distance to each other to very strict precision (nominally 100 billionths of an inch) by mechanical means. To hold this level of precision and stability over long periods of time (measured in months), rather sophisticated mechanical and electronic schemes, as well as a stable environment, are necessary. Our new development does away with all these complications, since it is a monolithic block insensitive to mechanical vibrations, where the tolerances of parallelism and distance have become part of a one-time manufacturing process, and it is no longer necessary to make any further adjustments for the life of the etalon cavity.

The single-crystal etalon cavity has two additional advantages not obvious in the above description. The first is, because the crystal has a large index-of-refraction, that the light gathering ability of the etalon cavity is increased by the second power of the refractive index (a factor of five in our case), which makes our new solid-state etalon more luminous than most of the large practical air-spaced etalon cavities presently available. Second, the electrooptic material optical thickness can be varied at will with a longitudinal electric field. This is equivalent to the mechanical movement of one of the mirrors of the etalon cavity. This property allows setting the etalon spacing for maximum transmission, as well as spectral scanning without the need of mechanical movement and without loss of parallelism.

After the proof-of-concept stage was completed, a detailed testing of the properties of large electrooptic crystal etalon cavities was begun. Among the properties studied, the behavior and stability of the multilayer mirror coatings of the electrooptic etalon under large electric fields are of special significance, since these coatings are not normally

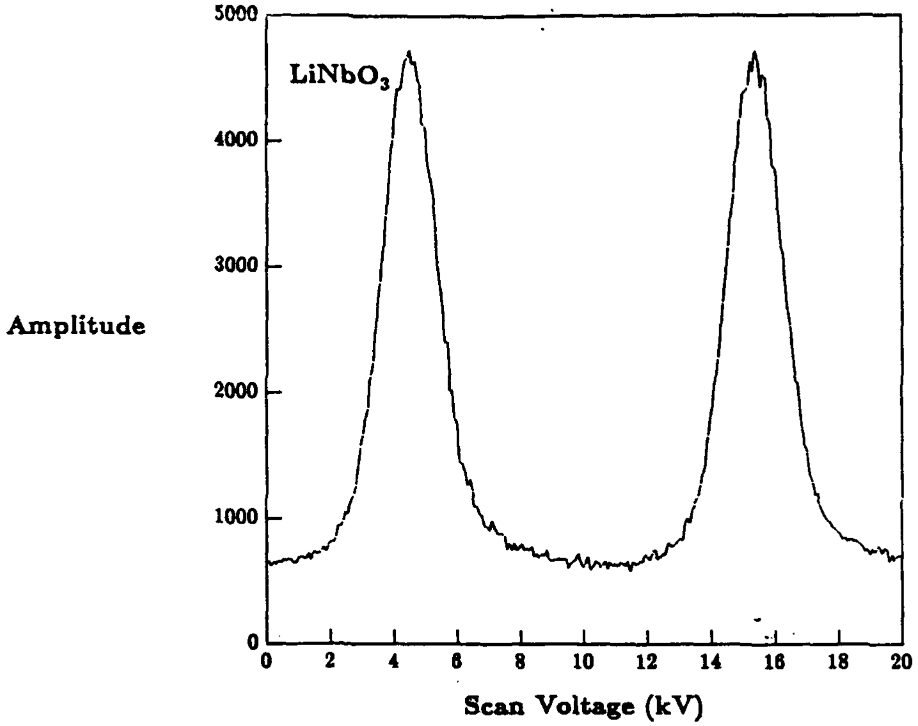

Fig. 9. Fringes from the monolithic electrooptic solid-state etalon. Single frequency HeNe laser measurements. Note the stability. From Hernandes and Clark, 1992.

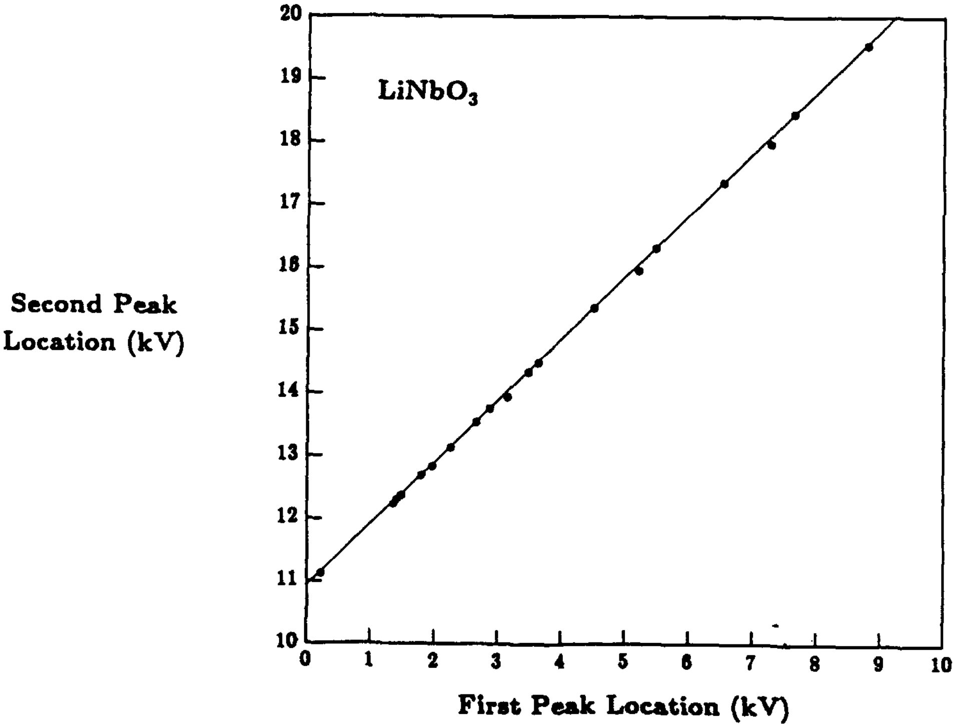

Fig. 10. Linearity of the electrooptic etalon cavity. This linearity is as good as the best piezoelectric scanning material used in the best air-gap etalons. From Hernandes and Clark, 1992.

operated under such conditions. The tests have shown that the presence of the operating field is relatively unimportant, when compared to the presence of humidity in the ambient air. This sensitivity to ambient moisture is in keeping with our previous experience with 'soft-mirror' coatings, such as the one in the present devices. subsequent operational tests have continued successfully in a chamber filled with dry air.

The experimental work came to a standstill due to construction and renovation of our laboratories by the University during the fall and winter of 1990/1991. The renovation resulted in a net gain, doubling our optical darkroom space, and making it possible to conduct our experimental work in more adequate quarters. This expansion of laboratory space is a recognition by the University of the place of our optical research in the educational process of graduate students.

Following the interruption for expansion, the basic investigations of the properties electrooptic etalon cavity have continued to the present. Other intrinsic properties, such as linearity of the unconstrained Pockel's effect as a function of voltage, the long-term stability, and stability of the transparent electrodes, etc. have been exhaustively studied. The results have shown the electrooptic crystal Pockel's effect to be extremely linear and reproducible and thus far the long-term stability tests have shown no anomalies. This result is quantitatively shown in Figure 10. A report on the findings on the electrooptic cavity is nearly ready for submission (Hernandez and Clark, 1992). Based on the knowledge gained with the prototype devices, more operationally-oriented cavities have been ordered to be used in field tests.

These monolithic cavities present unique advantages in the development of the high-luminosity high-resolution double-etalon modulator, or DEM (Hernandez, 1987; Hernandez and McCormac, 1988), because of their inherent stability and because they allow index-of-refraction coupling for the completed device. The combination of these two properties results in a smaller DEM instrument with enhanced stability of operation. This is an exciting development with a predictable potential, since the increased mechanical precision necessary for the successful operation of a DEM device appears to be provided by the electrooptic cavity. The machine shop work on the DEM has been completed, the instrument has been partially assembled, and it is ready to be tested for stability as a single-aperture Jacquinot spectrometer. The DEM has been part of AFOSR-supported long-term investigations of spectroscopic devices used for diagnostics and measurement of the upper atmosphere. The first DEM development was made for a high-luminosity device, with gains greater than 30 relative to an equivalent-area normal Fabry-Perot spectrometer. Further theoretical analyses on the spectral and spatial properties of the DEM as a high-resolution filter are in progress.

This grant has partially supported four graduate students in their research investigations leading to advanced degrees. The training of the new generation of scientist and engineers in these critical skill areas is the most valuable contribution to the nation that a research grant provides.

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