40th Anniversary of the First
Far-Infrared Fine-Structure Line Observations
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Introduction

Although 2015 is the 40th anniversary of the discovery of the first of the FIR astronomical fine-structure lines, I need to go back to a few years earlier to provide the setting in which the fine-structure observations came about.

***IN 1968 MY INFRARED ROCKET ASTRONOMY GROUP AT CORNELL SUCCESSFULLY LAUNCHED A FIRST LIQUID-HELIUM COOLED TELESCOPE. WHEN THE COLD TELESCOPE'S COVER WAS EJECTED AT AN ALTITUDE OF 130 KM, WE WERE SURPRISED BY A CONSIDERABLY HIGHER FIR SIGNAL THAN ANTICIPATED.[1] LATER THIS TURNED OUT TO BE DUE TO DIFFRACTED SUBMILLIMETER RADIATION FROM THE EARTH'S LIMB, REQUIRING MORE STRENUOUS BAFFING, BUT FOR A WHILE IT WAS PUZZLING, WAS WIDELY DISCUSSED, AND RAISED NEW QUESTIONS.

One of these was answered in an important paper by Vahe Petrosian, John Bahcall and Edwin Salpeter,[2] who examined whether far-infrared fine-structure emission from the Galaxy could account for the signal. Their 1969 paper predicted that C^+ emission and the two [OIII] lines at 88 and 52 microns would constitute the dominant sources of far-infrared fine-structure line emission, but concluded that fine-structure radiation alone could not account for the puzzling signals. ________________________________

***CAPITAL-LETTERED TEXT IS TO BE READ WITH SUCCESSIVE SLIDES.

***THE NEXT YEAR, 1970, VAHÉ PETROSIAN PURSUED THESE CALCULATIONS FURTHER[3]. WITH A NUMBER OF SIMPLIFYING ASSUMPTIONS, HE PROVIDED A FIRST INDICATION OF THE RELATIVE LINE STRENGTHS ONE MIGHT EXPECT IN THE SPECTRUM OF ORION AND OTHER HII REGIONS.

***TWO YEARS LATER, IN 1972, NASA HAD OFFERED OUR CORNELL GROUP THE OPPORTUNITY TO FLY INSTRUMENTATION ABOARD THE NASA LEAR JET.

Jim Houck in our group and I discussed this prospect. The infrared regime covers such a wide wavelength range that it made sense to split the range into two. Jim proposed that he and his students would carry out spectroscopic observations in the mid-infrared, and my students and I began to concentrate on observations in the far infrared. Both groups used a cryogenically cooled Dewar design that Jim had developed.[5]

***A LINE DRAWING OF THE OPTICAL LAYOUT OF THE LIQUID-HELIUM COOLED SPECTROMETER DISPLAYS ITS SIMPLE LINES. IT WAS SUFFICIENTLY COMPACT TO USE ON THE LEAR JET'S 30-CM TELESCOPE, BUT WOULD HAVE TO BE OUTFITTED WITH A QUITE DISTINCT SET OF DETECTORS, FILTERS AND OTHER FEATURES TO WORK EFFECTIVELY IN OUR RESPECTIVE MID- AND FAR-INFRARED WAVELENGTH RANGES.

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***THE FIRST OF MY GRADUATE STUDENTS TO WORK IN FAR-INFRARED SPECTROSCOPY WAS DENNIS BRIEN WARD, A YOUNG CANADIAN. HE OUTFITTED THE SPECTROMETER FOR THE FAR INFRARED WITH GALLIUM-DOPED GERMANIUM DETECTORS, MADE ALL LABORATORY AND IN-FLIGHT CALIBRATIONS, AND OBTAINED THE FIRST ASTRONOMICAL DATA.

Between September 1972 and April 1975, Dennis had six observing runs, involving a total of 63 flights on the Lear jet, each lasting up to 130 minutes from takeoff to landing, and yielding up to an hour of observing time. All flights took off from, and returned to, the NASA Ames Research Center, just South of San Francisco.

***THE LEAR JET CABIN WAS ABOUT THE SIZE OF A TAXI CAB. ONLY FOUR PEOPLE COULD FIT INTO THE AIRCRAFT WITH THE TELESCOPE AND DATA RECORDING SYSTEM ABOARD. SEEN HERE IS GEORGE GULL, OUR HIGHLY VERSATILE TECHNICIAN, WHO FLEW ALONG WITH DENNIS ON MANY FLIGHTS, AND ALSO FLEW WITH MEMBERS OF JIM HOUCK'S GROUP.

***OF THE FOUR OCCUPANTS OF THE PLANE, TWO WERE TEST PILOTS, REQUIRED BECAUSE THE AIRCRAFT HAD AN UNCONVENTIONAL HOLE CUT IN ITS SIDE FOR THE TELESCOPE TO LOOK OUT.

***OF THE TWO ASTRONOMERS ONBOARD, ONE CONTROLLED THE SPECTROMETER, THE TELESCOPE AND ITS POINTING.

***THE OTHER, MONITORED THE INCOMING DATA. OXYGEN MASKS WERE MANDATORY AT ALTITUDE.

*** DENNIS WARD'S INITIAL EFFORTS INVOLVED OBTAINING CONTINUUM SPECTRA OF FIR SOURCES, WHICH NOBODY HAD YET OBTAINED. PREVIOUS WORK HAD USUALLY CONCENTRATED ON THE SIMPLER PROBLEM OF FIR PHOTOMETRY AND MAPPING. THE SPECTRAL

RESOLUTION OF THE SYSTEM WAS ABOUT 1.3 MICRONS AT 80 - 90 MICRONS, A RESOLVING POWER OF ROUGHLY 65, MATCHED TO OUR 5 ARC MINUTES SQUARE BEAM. THE MOON AND VENUS WERE USED AS CALIBRATION SOURCES TO ASSURE THAT WE CORRECTLY ACCOUNTED FOR ANY RESIDUAL ATMOSPHERIC TRANSMISSION PROBLEMS EVEN AT THE LEAR JET'S 13 -- 14KM ALTITUDES.

At some point, Dennis suggested that we look for the 88 micron [O III] line, where our gallium-doped germanium detectors were quite sensitive. I didn't think we had the faintest chance of success with our spectral resolving power of only 65. But if a student really wanted to try something daring, I certainly was not going to discourage it. So I agreed Dennis should try.

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***THIS LED TO THE DISCOVERY OF THE 88 MICRON FINE STRUCTURE LINE, ON THE LEFT, IN EARLY 1975, IT WAS A SUFFICIENTLY IMPORTANT FINDING TO DEMAND QUICK PUBLICATION AND COMPLETION OF DENNIS'S PHD THESIS WITHIN A FEW MONTHS, THAT SAME YEAR. IT ALSO LED TO A WHOLE NEW RESEARCH DIRECTION FOR MY STUDENTS AND ME FOR THE FOLLOWING SEVEN OR EIGHT YEARS.

FOR M17 IN THE TOP PANEL ON THE LEFT, WE DETECTED THE 88 MICRON FEATURE IN EACH OF SEVEN INDIVIDUAL SPECTRA, WHOSE INTEGRATED FLUX WAS 8 SIGMA ABOVE NEIGHBORING POINTS. IN THE NEXT PANEL DOWN, ON M42, NO COMPARABLY STRONG FEATURE WAS APPARENT. THE BROAD DIP AT 90 MICRONS, SEEN ALSO IN THE SPECTRA OF VENUS AND THE MOON, IS DUE TO ATMOSPHERIC ABSORPTION ABOVE THE AIRCRAFT.

EVEN AS WE WERE REFINING OUR TECHNIQUES TO CHANGE OVER TO FURTHER FINE-STRUCTURE LINE WORK --- WHICH ENTAILED INCREASING OUR SPECTRAL RESOLVING POWER FROM ABOUT 65 TO 150 --- WE WERE FOLLOWING UP WITH IMPROVED OBSERVATIONS OF THE 88 MICRON LINE IN A NUMBER OF OTHER GALACTIC HII REGIONS, AS SEEN IN THE SPECTRA DISPLAYED ON THE RIGHT.

* * *

***A FACTOR THAT ENABLED DENNIS TO COMPLETE HIS THESIS SO QUICKLY WAS A REMARKABLY COMPLETE PAPER PUBLISHED BY JANET P. SIMPSON AT THE NASA AMES RESEARCH CENTER, THAT SAME YEAR ONLY FIVE YEARS AFTER COMPLETING HER PHD THESIS AT BERKELEY.[4] SHE GENEROUSLY SHARED HER PAPER WITH US EVEN BEFORE PUBLICATION. OUR M42 AND M17 88 MICRON LINE-STRENGTHS WERE IN REASONABLE AGREEMENT WITH HER PAPER'S PREDICTIONS AND CONSIDERABLY FAINTER THAN VAHE PETROSIAN HAD PROPOSED BASED ON HIS HIGHER ASSUMED [OIII] ABUNDANCES.

***JANET'S PAPER READ LIKE AN ASTROPHYSICAL GUIDE ON HOW TO INTERPRET FINE-STRUCTURE SPECTRA; THE SIMPLIFYING ASSUMPTIONS THAT COULD BE APPLIED; HOW THE AVAILABILITY OF TWO DIFFERENT SPECTRAL LINES FROM A GIVEN IONIZED SPECIES COULD PROVIDE USEFUL INSIGHT ON THE TEMPERATURE AND DENSITY OF THE REGIONS WITHIN WHICH THEY WERE EMBEDDED.

If several different chemical species inhabited the same HII region, an observer could begin to estimate relative chemical abundances as well, although those would then depend also on the relative abundances of an element's major ionic components. And where two spectral features of a given element were available, one might begin searching for optical depths effects. Since 1968, reliable spontaneous transition probabilities for the major FIR fine-structure lines were finally at hand, making such calculations possible.[4a]

With Janet Simpson's approach we could immediately start asking and sometimes even answering astrophysical questions, even as the data were just becoming available.

*** THE FOLLOWING YEAR, 1976, THE EUROPEAN GROUP OF BALUTEAU, BUSOLETTI, ANDEREGG, MOORWOOD AND CORON, PUBLISHED THEIR OWN DETECTION OF THE 88 MICRON LINE, WITH A MICHELSON INTERFEROMETER FLOWN ON THE KUIPER AIRBORNE OBSERVATORY. WITH THEIR HIGHER SPECTRAL RESOLVING POWER OF 5000, THEY ESTABLISHED THE LINE'S WAVELENGTH MUCH MORE ACCURATELY, TO BE 88.35 MICRONS[6].

* * *

***THE DETECTION OF THE 88 MICRON LINE OF [OIII] BY DENNIS WARD WAS SOON FOLLOWED IN 1977 BY THE DETECTION OF ITS 52 MICRON [OIII] COUNTERPART BY DENNIS'S SUCCESSOR, MY NEXT GRADUATE STUDENT GARY MELNICK[7].

***ONCE HE HAD SUCCEEDED IN THIS, GARY ALSO OBTAINED THE FIRST DETECTION OF THE 63 MICRON [OI] TRANSITION, ALMOST AS THOUGH HE WAS AGAIN OPENING A DOOR FOR HIS SUCCESSOR AS PHD STUDENT IN OUR GROUP, GORDON STACEY, WHO WENT ON TO DETECT ITS COUNTERPART EMISSION AT 145.5 MICRONS, TO WHICH I'LL RETURN LATER.

Gary Melnick's thesis work, with its first observation of the 63 micron line, had been partially suggested to us also by a preprint we received of a paper by Jesse K. Hill and David Hollenbach in 1978[8].

They had theoretically investigated domains lying just outside expanding HII regions. Because the pressures in the centrally heated HII regions are so high, one knew that the regions must be expanding, and this was likely to lead to complex physical conditions involving shocks, ionization fronts, and mixtures of neutral and ionized atoms immediately ahead of the expanding HII front. Part of this mix would be collisionally excited neutral oxygen, which could be cooling these regions significantly through the 63-micron fine-structure transition.

Ted Gull, a former student of mine and brother of George Gull on our team, also let us know prior to publication, that his optical observations of the 6300 Angstrom [OI] line indicated a rising fraction of neutral relative to ionized oxygen as one crossed the Orion bar away from θ Orioinis[9]. All of this gave encouragement to searching for the [OI] 63-micron emission.

As the 1970s were ending, and with the 88, 52 and 63-micron features all successfully detected, we turned our attention to discovering the C^+ feature. This turned out to be by far the most difficult set of observations we undertook. Three circumstances conspired:

First, the gallium-doped germanium detectors we had previously used did not work at the far longer wavelengths at which C^+ radiated, unless they were stressed to a point where they easily broke. Many different laboratories were of help with advice, procedures, and material. We had to design detector housings that would hold the size detector we required in our Dewar, and the housing had, at the same time, to provide the high stresses necessary to provide detector response out to the longest required wavelengths. Where the leads to the detectors had to be attached, we needed to implant boron through high voltage bombardment followed by annealing. Finally, the liquid helium coolant had to be pumped to lower detector temperatures to about 2 degrees Kelvin[10].

Second, for strange historical reasons, the frequency of the C^+ line quoted in the literature ever since 1928, when it had been derived from laboratory spectra obtained in the visible and UV, was 64.0 cm^{-1} corresponding to ~156.25 microns, and thus painfully misleading, both in the cited wave number and the wavenumber's accuracy implied by its last digit.[11]

Third, when we did detect the line, the emitting regions turned out to be far more extended than had been thought, and this led to difficulties in its detection, particularly with large telescopes.

***RAY RUSSELL, A POST-DOC IN MY GROUP AT THE TIME, BEGAN CONCENTRATING ON THE MISNAMED 156 MICRON C^+ EMISSION AROUND EARLY 1979.

Using the Lear Jet, Ray and I searched for the C^+ line in vain for a whole series of flights, between the then-anticipated wavelengths of 152 and somewhat beyond 156 microns. On November 27, 1979, just before the last planned flight in our series, I was speaking on the phone with Bill Forrest who then was working at Cornell with Jim Houck. He mentioned he'd heard the line might lie out around 158 microns. So,

** WE SCANNED THE SPECTRAL RANGE OUT TO BEYOND 158 MICRONS, THAT NIGHT, AND IMMEDIATELY FOUND THE EMISSION FEATURE. WE THEN HAD TO BEG THE NASA AMES PEOPLE TO GIVE US AN ADDED DAYTIME FLIGHT, THE NEXT NOON, SO WE COULD GET A SPECTRUM OF VENUS AT THE SAME WAVELENGTHS, WHERE ONLY CONTINUUM AND NO C^+ EMISSION WAS EXPECTED, AND WE COULD BE SURE THAT WE WERE NOT JUST OBSERVING SOME UNANTICIPATED ATMOSPHERIC FEATURE.

At this point, a new uncertainty arose.

***MIKE WERNER, WHO HAD BEEN MY FIRST PHD STUDENT, A DECADE EARLIER, OFFERED SOME KAO OBSERVING TIME HE HAD BEEN GRANTED SO WE MIGHT JOINTLY STUDY THE C^+ EMISSION FURTHER, AT THE THREE-TIMES-HIGHER SPATIAL RESOLUTION THAT THE KAO'S 91-CM TELESCOPE OFFERED. IT SOUNDED LIKE A GREAT OPPORTUNITY AND I MMEDIATELY AGREED!

***ON THIS OCCASION, OUR OBSERVATIONS OF M17 WERE CARRIED OUT ON FIELDS OF VIEW ROUGHLY ONE ARC MINUTE ON A SIDE WITH A 6 ARC MINUTE CHOPPER THROW.

The results of this KAO flight were alarming! We detected absolutely nothing! I couldn't believe it! Had we made some horrible mistake in our Lear Jet observations? In our next planned series of Lear Jet flights, we repeated our observations on M17 and, sure enough, found our usual signal booming in.

Gradually, it dawned on us that, in our KAO observations the telescope's restricted 1 arc minute fields of view and 6 arc minute chopper throw had simply been chopping between two regions, both close to the peak of the M17 brightness distribution, where both beams were pointed at regions almost equally luminous. In contrast, on the Lear Jet, our field of view was 4 by 7 arc minutes and our chopper throw 11 arc minutes.

**WE PUBLISHED A PAPER WITH MIKE WERNER ANNOUNCING THAT THE C^+ EMISSION FROM M17 STRETCHED OUT FAR BEYOND THE CONFINES OF THE OPTICAL HII EMISSION, IN WHAT WE DESCRIBED AS A "GIANT

[CII] HALO." YOU CAN SEE THE SIGNAL DROPPING AT THE LAST TWO BOLD POINTS TOWARD THE UPPER LEFT[12].

**A MORE THOROUGH MAPPING THAN OURS OF THE M17 C^+ EMISSION, ONLY TOOK PLACE SEVEN YEARS LATER WHEN THE JAPANESE GROUP OF MATSUHARA AND COLLEAGUES JOINED BY FRANK LOW, LAUNCHED A BALLOON FLIGHT FROM PALESTINE, TEXAS IN JUNE 1988[15].

* * *

Meanwhile, our 158-micron findings and the existence of strong 63-micron [OI] emission, which also had to come from beyond the confines of ionized hydrogen regions began to shed light on shocked regions outside the bounds of the expanding HII domains, where the dissociation of molecular hydrogen had been predicted, ten years earlier, in a joint paper by David Hollenbach, Michael Werner, and Edwin E. Salpeter[13].

** WE DISCUSSED OUR C^+ FINDINGS WITH DAVID HOLLENBACH, WHO AT AN AAS MEETING IN BOULDER COLORAD EARLY THAT SUMMER, SUGGESTED THAT HEATING OF GRAINS BY 6 - 13.6 eV PHOTONS LEAKING OUT OF THE HII REGION COULD BE EXCITING THE WIDELY DISTRIBUTED [OI] 63-MICRON AND C^+ 158-MICRON FEATURES IN WHAT HE, HERE, BEGAN CALLING "PHOTODISSOCIATION REGIONS." [14]

* * *

The next question to arise in our group was just how far these "giant C^+ haloes" actually stretched? Did they pervade the entire interstellar medium? The M17 observations had not ruled out that faint C^+ domains might stretch far beyond the range we had been able to map.

For over a decade it had been postulated that the general interstellar medium close to the Galactic plane cooled itself through C^+ emission. An estimate of this had been published by Pottasch, Wesselius, and van Duinene in 1979, based on the strength of ultraviolet absorption lines originating fro the upper fine structure level $^2P_{3/2}$ of C^+ [16]. But we till were not sure how far from the central Galactic plane this emission might stretch.

***TO INVESTIGATE THIS QUESTION, GORDON STACEY UNDERTOOK WHAT I BELIEVE WAS ONE OF THE NICEST LEAR JET OBSERVATIONS OUR GROUP HAD TRIED, GIVEN THE RELATIVELY PRIMITIVE TECHNIQUES AVAILABLE TO US AT THE TIME. TO DETERMINE HOW FAR THE C^+ EMISSION ACTUALLY EXTENDED WE WOULD NEED TO CHOP AGAINST A REGION WE COULD BE CERTAIN TO BE FREE OF C^+ EMISSION.

For over a decade it had been postulated that the general interstellar medium close to the Galactic plane cooled itself through C^+ emission. An estimate of this rate had been published by Pottasch, Wesselius, \& van Duinen in 1979, based on the strength of ultraviolet violet absorption lines originating from the upper fine structure level $^2P_{3/2}$ of C^+ [16]. But we still were not sure how far from the central Galactic plane, this emission might stretch.

***THE MOON CROSSES THE GALACTIC PLANE TWICE A MONTH. ONE OF THESE TIMES WAS TO BE ON FEBRUARY 18, 1982. WE SCHEDULED OUR NEXT SERIES OF FLIGHTS TO ALLOW US TO COVER THE GALACTIC PLANE CROSSING. WE WOULD NEED TO PRACTICE THIS SOMEWHAT COMPLICATED FLIGHT, WHICH WOULD HAVE TO BE TIMED ACCURATELY TO THE MINUTE TO GET THE MAXIMUM EXPOSURE OF THE MOON GRADUALLY MOVING AWAY FROM THE GALACTIC DISK, DURING THE ROUGHLY 35 MINUTE MAXIMUM OBSERVING TIME THE LEAR JET WOULD OFFER[17].

Gordon Stacey carried out this observation by chopping between the Moon's dark limb and a succession of points on the Galactic disk at a fixed angular distance from the lunar limb, as the Moon receded from the disk. The Moon would emit no C^+ emission. The Galaxy would. So, subtracting the Moon's signal from that of the Galaxy's would tell us the galactic latitude at which the Galaxy ceased emitting in the C^+ line.

** THIS GAVE US A PROFILE OF C^+ EMISSION AT LEAST AT ONE LONGITUDE OF THE MILKY WAY. NEAR GALACTIC LONGITUDE 8 DEGREES OUR MEASUREMENTS YIELDED A DISK HALF WIDTH OF ONLY ABOUT 1/6 OF A DEGREE, WHICH SURPRISED US BECAUSE IT WAS RATHER NARROWER THAN THE FAR INFRARED DUST EMISSION WHICH PROVIDED AN INDEPENDENT MEASURE OF THE GAS AND DUST DISTRIBUTION.

** GORDON THEREFORE UNDERTOOK TO MEASURE THE C^+ EMISSION HALFWIDTH AGAIN AT OTHER LONGITUDES, THIS TIME RESORTING TO A MORE CONVENTIONAL TECHNIQUE OF OBSERVATIONALLY STEPPING THE LEAR JET TELESCOPE ACROSS THE GALACTIC DISK, USING GUIDE STARS, PRIMARILY AT TWO LONGITUDES WHERE CONVENIENT GUIDE STARS WERE AVAILABLE. A THIRD SCAN WAS CARRIED OUT AT A LONGITUDE CLOSE TO OUR ORIGINAL OBSERVATIONS. [18]

The possibility of using this simpler method rested on the earlier occultation measurements having shown that if we started our scans far enough from the Galactic plane, we could be sure we were initiating the scans at Galactic latitudes devoid of significant C^+ emission. This second Lear Jet campaign involving six flights found a considerably larger half width of roughly 0.34 degrees, but also a total flux roughly eight times lower --- suggesting that the earlier measurements might have fortuitously crossed the plane at a longitude containing a densely packed set of molecular clouds. Our duplicating scan carried out near the original region also showed a sharper peak this time --- though not at as high a luminosity.

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**TO OBSERVE FAINTER LINES AT HIGHER SPECTRAL RESOLUTION, WE CONSTRUCTED A LAMEALLAR GRATING INTERFEROMETER WITH RESOLVING POWER ~700, FOR USE ON THE KAO, IN TANDEM WITH OUR LEAR JET SPECTROMETER SERVING AS A MONOCHROMATOR STAGE. THOUGH CRUDE, THIS NOVEL DEVICE COST LESS THAN $2,000 IN PARTS AND MACHINING EXPENSES, TOOK ONLY 7 WEEKS TO DESIGN, CONSTRUCT, TEST, AND FLY ON THE KAO, AND SERVED ITS PURPOSE WELL.

** WE DETECTED AND OBTAINED THE WAVELENGTH OF THE 145.5-MICRON LINE IN M42 AT LEFT, AND FOLLOWED UP WITH WIDER FIELD OF VIEW WORK ON THE LEAR JET, AT RIGHT. FROM THIS AND OTHER M42 DATA, GORDON DEDUCED THE OPTICAL DEPTH OF ITS KNOWN 63-MICRON EMISSION TO BE ABOUT 2.

By 1985, ten years after the initial detection of FIR fine-structure lines, assembling the basic observational tools for gaining astrophysical insight was reaching completion.

**OF COURSE, OTHER GROUPS BESIDE OURS HAD ALSO BEEN DEEPLY INVOLVED. ALAN MOORWOOD AND HIS COLLEAGUES HAD DETECTED THE [NIII] 57 MICRON LINE IN 1980. THE TWO IMPORTANT [NII] LINES AT 122 AND 205 MICRONS, HOWEVER, WERE ONLY DETECTED MUCH LATER IN 1988 AND 1991.

In addition, ongoing submillimeter work had been critical to studying cold gas clouds, as were mid-infrared data on rather warmer regions than the FIR observations covered. In the mid-infrared, the US group of Jim Houck, and the European group headed by Jean-Paul Baluteau and Alan Moorwood were particularly active in completing the inventory of the most important fine structure lines.

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***BY THEN THE GROUP OF CHARLIE TOWNES AND REINHARD GENZEL AT BERKELEY WAS ALSO ADDRESSING FINE STRUCTURE TRANSITIONS ALONG WITH THE FAR-INFRARED MOLECULAR WORK THEY HAD EARLIER BEEN PURSUING.

***THEIR WORK ON EXTRAGALACTIC OBSERVATIONS OF THE FIR INFRARED FINE-STRUCTURE LINES WAS NOW PROVIDING AT LEAST A FIRST LOOK AT PROCESSES GOING ON IN NEARBY GALAXIES[19].

I believe, our Cornell group was lucky in that we happened to have chosen to mainly work with the Lear Jet, where we could easily observe all the Galactic fine structure lines with the small telescope's larger field of view and huge chopper throw. This wasn't by design, but rather that other groups were competing aggressively for use of the larger KAO 91 cm aperture telescope, and none of them wanted to work with a mere 30-cm telescope. We also were lucky in working with very low spectral resolving power. It took the competition much longer to build the complex high-spectral-resolution instruments and make them work.

We all knew, however, that a next generation of more powerful instruments would be needed to do more. More sensitive detectors, a clearer view of the Universe obtained from space, where one no longer had to worry about atmospheric absorption or emission, would lead to improved detection. In the FIR, the Infrared Space Observatory, ISO, and the Herschel telescope successively have offered these advantages, and Herschel additionally provided higher angular resolution. SOFIA is also beginning to make contributions. All this took another thirty years to develop, and that is where we stand, today. What the next practical steps might be is for the current generation to decide.

Appendix: The misinformed spectral line frequency for the FIR C^+ transition.

The faulty line frequency of 156 microns that people were using until about 1980 came from optical and ultraviolet spectra of singly ionized carbon obtained by Alfred Fowler and E. W. H. Selwyn in 1928 ("Further Investigations of the Spectrum of Singly-Ionised Carbon (C II)" by A. Fowler, E. W. H. Selwyn, Proc. R. Soc. London A 1928, 120, 312-326; DOI: 10.1098/rspa.1928.0152). These authors measured lines at wave numbers 196659 and 196595 cm^{-1}, and concluded the difference was 64.0 cm^{-1}, corresponding to precisely 156 micons. Had they written this simply as 64 cm^{-1} this would not have been misleading, nor if they had more explicitly emphasized in their paper that other sets of laboratory measurements listed in their Table III, on page 321 had yielded values in the range of 62.7 to perhaps as high as 65.2 cm^{-1}, corresponding to wavelengths ranging from about 153.4 to 159.5 microns. But because they had emphasized their value of 64.0 cm^{-1}, Gerhard Herzberg cited this value in his book on ``Atomic Spectra and Atomic Structure" in 1937 and later editions, so that the wavelength of 156 microns then propagated on for the another forty years.

But in 1963 Bengt Edlén published a laboratory in the ultraviolet range, between 594 and 1066 Angstrom units, in which he obtained C^+ spectra from impurities in

his setup. Among 19 spectral lines for which he obtained accurate data, seven pairs emerged whose wave numbers centered around 63.41 cm^{-1} and an average wavelength of about $157.69^{+0.01}_{-0.02}$ microns[20].
Our group was not aware of those data at the time, but they may have been available to Lawrence T. Greenberg of The Aerospace Corporation, who apparently mentioned to B ill Forrest that the wavelength of C^{+} might be as long as 158 microns.

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