(NASA-CR-158052) INFRARED HETERODYNE SPECTROSCOPY FOR ASTRONOMICAL PURPOSES (California Univ.) 6 p HC A02/MF A01 CSCL 03A
N79-15875
Unclas
G3/89 42216

C. H. Townes

Infrared Heterodyne Spectroscopy for Astronomical Purposes*

University of California, Berkeley, CA
USA

Heterodyne detection has a theoretical sensitivity disadvantage by comparison with direct detection (photon counters or bolometers), but an actual practical advantage when either long wavelength or very high spectral resolution is involved. For unpolarized radiation the ideal theoretical ratio of sensitivity of heterodyne detection compared to direct detection is

$$\left(\frac{e^{-h\nu/kT}}{2}\right)^{1/2}$$

Here ν is the frequency, T the effective temperature of background radiation falling on the detector, and it is assumed $h\nu >> kT$. For polarized radiation at low frequencies such that $h\nu << kT$, the ideal theoretical sensitivity of the two types of detection is identical. However, in the microwave region, where $h\nu << kT$, heterodyne detection has an important practical advantage. This is that heterodyne detectors exist which come reasonably close to the theoretical sensitivity limit, while photon counters or bolometers miss this limit by a wide margin, so that in practice heterodyne detection is much more sensitive and generally used at these low frequencies. As the frequency is increased from the microwave region, not only does the theoretically expected ratio of sensitivity decrease monotonically, but also the quality of technical devices available varies considerably. At 10 microns wavelength and shorter, detectors of both types are available which under some conditions come within a factor of 2 of ideal performance.

The availability of good detectors and good lasers for local oscillators has meant that, while the longer infrared wave-lengths may be more favorable in principle, the 10 micron atmospheric window has been the most fruitful region for infrared astronomical work with heterodyne detection. Even though for any bandwidth a direct detector should in principle be about twenty times more sensitive than heterodyne at 10μ

---

wavelength, direct detectors miss ideal sensitivity for very narrow bandwidths by a substantial factor and heterodyne detectors can be more sensitive. However, with continuing detector development one must in the long run look to infrared heterodyne detection primarily for convenience rather than for ultimate sensitivity, in particular convenience and efficiency in obtaining very high spectral resolution. Heterodyne detection translates the problem of spectral resolution into a lower frequency domain where it is easier to build very narrow filters; with direct detection high resolution must be obtained essentially by the use of very long pathlength differences before detection, and these can be very awkward when it is desired to resolve bandwidths less than about 0.01 cm^{-1}.

While primarily a narrow band technique, heterodyne spectroscopy for astronomical purposes in the 10 micron region requires bandwidths which are very large by comparison with the normal situation at microwave frequencies. We have built a 64-filter system of bandwidth about 1300 MHz; nevertheless, for a fixed frequency local oscillator at 10μ wavelength, even the earth's orbital motion can produce doppler shifts which change the frequencies of lines to be observed by several times the width of this set of filters. Furthermore, although tunable laser local oscillators can be built which come close to the performance desired for heterodyne spectroscopy, they still do not conveniently give the required stability and power. Hence heterodyne spectroscopy in this region is somewhat restricted by the limited frequency coverage which is readily available. Nevertheless, the many lines of different isotopes of CO_2 plus observations at carefully chosen times of the year allow high quality astronomical spectroscopy with a reasonable coverage of frequencies.

Heterodyne infrared astronomy has been carried out primarily by two groups, one at the University of California at Berkeley and the University of Toronto and the other at Goddard Space Flight Center in Greenbelt, Maryland. In addition to CO_2 lasers, the latter group has also used some solid state tunable lasers.[1] The best available detectors are mercury cadmium telluride photodiodes built by Spears of the Lincoln Laboratories.[2] Their quantum efficiencies reach values near 0.5 and in an overall system an effective quantum efficiency, taking into account optical losses and amplifier noise, of about 0.25 has been demonstarted.[3]

A number of the initial uses of 10 micron heterodyne spectroscopy were for the study of planetary molecular spectra.[4-10] Work on CO_2 in Mars and Venus revealed nonthermal emission of CO_2 in the high atmospheres of these planets,[5] with linewidths as small as about $10^{-3}cm^{-1}$. At resolving powers as high as about 10^7, the shapes of these anomalous emission lines as well as those of absorption lines of CO_2 have been studied in some detail. These have provided good information on the pressure-temperature curve for the atmosphere of Mars,[7] and on the winds in the upper atmosphere of Venus,[6,8] whose doppler velocities have been measured to a precision of about 5 m/sec. In the stratosphere of Venus, the observations show that winds circulate about the equator with a retrograde velocity of about 90 m/sec. However, this velocity varies about 50% on a time-scale of 4 or 5 days. At mesospheric altitudes, the winds are accelerated from the subsolar point towards the antisolar point, again with peak velocities near 100 m/sec. There appear to be also vertical motions of the atmosphere of Venus as large as a few tens of meters per second. While instruments actually entering the planet's atmosphere can give more precise data for a variety of parameters, the cheaper and more extensive atmospheric information which can be obtained by a series of heterodyne observations from the ground can give detailed information on daily wind patterns and variations. On the planet Jupiter, intense ammonia emission from regions above the troposphere has been reported.[9] However, this must be a transient phenomenon since a number of other searches have resulted in no ammonia detection of this type.[11]

Absorption lines of ammonia have been detected by Betz et al.[12] in circumstellar material around the star IRC +10216. Three lines of ammonia are shown in Figure 1 with a spectral resolution of about 7×10^{-4} cm^{-1}. These lines differ in width and shape, and there are additional features (marked A, B and C) which seem to be above random fluctuations. While these observed lines are all metastable, a nonmetastable line has been searched for and found to be very much weaker, indicating decay between collision times and hence giving information on the molecular density where ammonia occurs. Somewhat similar absorption lines have been found in the star VY Canis Majoris.[13] Central doppler velocities in this case correspond to -4.5 km/sec, essentially the same as prominent features of H_2O and OH masers associated with this star. While the data from VY Canis Majoris is still being analyzed, its lines are remarkably similar to those from IRC +10216, with the (6,6) line being substantially broader than the (2,2) line, and the absorption depth being approximately 10%. Infrared heterodyne spatial interferometry has recently shown that a small central hot region in both of these stellar complexes, presumably the star itself, emits approximately 10% of the total infrared energy, the remainder coming from a dust shell of diameter approximately 0.8 second. The dust shells appear to have optical depths near unity. Analysis of the lines shows that for IRC +10216 most of the detectable ammonia lies between the central star and the much larger dust envelope. Abundance and densities also deduced from the spectral lines show that the NH_3 abundance is more likely in equilibrium with the cooler temperature of the dust than with the temperature of the central star.[12]

While the total amount of astronomical spectroscopy carried out so far by infrared heterodyne techniques is still small, the discovery of a number of very narrow lines and the importance of details of their shapes make this field a promising one for the future. Technical developments, particularly with respect to tunable or modulated laser oscillators and less noisy amplifiers can be expected over the next few years which will make the technique considerably more powerful and convenient, so that it may in the future be a rather widely used type of spectroscopy.

REFERENCES

1. Mumma, M., Kostiuk, T., Cohen, S., Buhl, D., and von Thuna, P.C. Nature 253, 514 (1975)
2. Spears, D.L. Infrared Physics 17, 5 (1977)
3. Betz, A.L. Thesis, University of California, Berkeley (1977)
4. Peterson, D.W., Johnson, M.A., and Betz, A.L. Nature 250, 128 (1974)
5. Johnson, M.A., Betz, A.L., McLaren, R.A., Sutton, E.C., and Townes, C.H. Ap. J. 208, L145 (1976)
6. Betz, A.L., Johnson, M.A., McLaren, R.A., and Sutton, E.C. Ap. J. 208, L141 (1976)
7. Betz, A.L., McLaren, A.C., Sutton, E.C., and Johnson, M.A. Icarus 30, 650 (1977)
8. Betz, A.L., Sutton, E.C., McLaren, R.A., and McAlary, C.W. Proc. Symposium on Planetary Atmospheres, Ottawa, p. 29 (1977)
9. Kostiuk, T., Mumma, M.J., Hillman, J.J., Buhl, D., Brown, L.W., and Faris, J.L. Infrared Phys. 17, 431 (1977)
10. Mumma, M.J., Abbas, M.M., Buhl, D., and Kostiuk, T. Bull. Am. Astron. Soc. 10, 555 (1978)
11. Betz, A.L., private communication

12. Betz, A.L., McLaren, R.A., and Spears, A.L. Ap. J., to be published
13. Betz, A.L., and McLaren, R.A., private communication

*This work is supported in part by NASA Grants NGL 05-003-272 and NGR 05-003-452

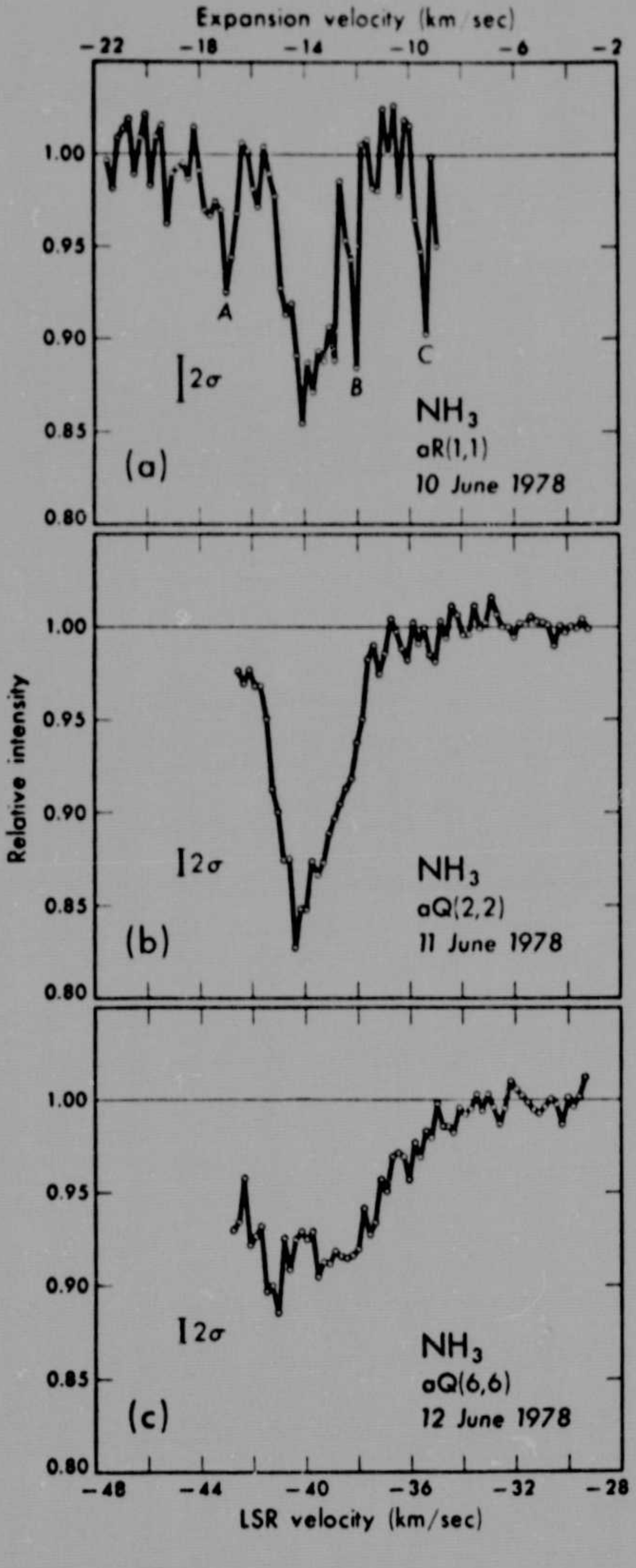

Figure 1: NH$_3$ absorption lines in IRC +10216 detected by Betz et al.[12] using heterodyne techniques with resolution 0.22 km/sec or 7 x 10^{-4}cm^{-1}. These lines are part of ν_2 band near 10.5μ wavelength.