N O T I C E

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INFRARED ASTRONOMY

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The present report covers the latter half of the eighteenth year of operation of an observational program in infrared astronomy under NASA Grant NGL 05-002-207. The program supported by this grant is currently carrying out work in two broad wavelength ranges, the near infrared (1 - 10 μm) and the millimeter.

A. Near Infrared Studies

The near infrared work concentrates largely on the use of the 5 m Hale telescope in spectroscopic and photometric studies of extragalactic sources. The photometric studies are characterized by being long range and attempting to measure unbiased and large samples of objects in order to understand statistical trends. In particular, in collaboration with R. Green, we have measured all the quasars found by Green on the basis of purely optical discriminators. So far we have measured the total sample of > 100 quasars at 1.2, 1.6 and 2.2 μm. A subset has been observed at 3.5 and 10 μm. During the last six months we have put all the visual and infrared data into a computer so the processing of this sample can be carried out on a large scale. This chore is now completed and analysis should start soon.

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In another related program in collaboration with B. Margon and G. Chanan, we have measured the infrared properties of X-ray quasars discovered in the study of serendipitous sources found in Einstein Observatory observations of other sources. Thus far we have obtained JHK photometry of ~30 such quasars. Figure 1 shows the visual to 2.2 μm spectral index of these sources, compared to that of an optically selected sample of quasars. Based on a preliminary analysis of these data, it seems that the X-ray selected quasars do not differ substantially in their infrared properties from the optically selected quasars.

One of the most puzzling observations relating to quasars is the discrepant values of the ratios of hydrogen emission line strengths. Previously, this group added significant data in studies of hydrogen lines in quasars which have been redshifted to the infrared. We have now extended these observations by making nearly simultaneous measurements of Pα, Hα, and Hβ for 18 Seyfert galaxies; in addition Lα was detected in eight of these galaxies. The data are shown in figure 2. In contrast to QSOs, the Pα/Hα/Hβ line flux ratios of Seyferts are in most cases consistent with reddened case B recombination spectra. Four galaxies have QSO-like spectra with Pα/Hβ ≈ case B and Hα/Hβ > case B. No clear intermediate cases are seen. Lα/Hβ is always less than 35. In some cases, it is consistent with the reddening derived from Pα/Hβ or Hα/Hβ. In others it falls below the reddening curve. Extinction by dust external or internal to the emission line regions can explain most of the observed ratios, although the reddening determined from the hydrogen lines does not correlate well with that determined in other ways.

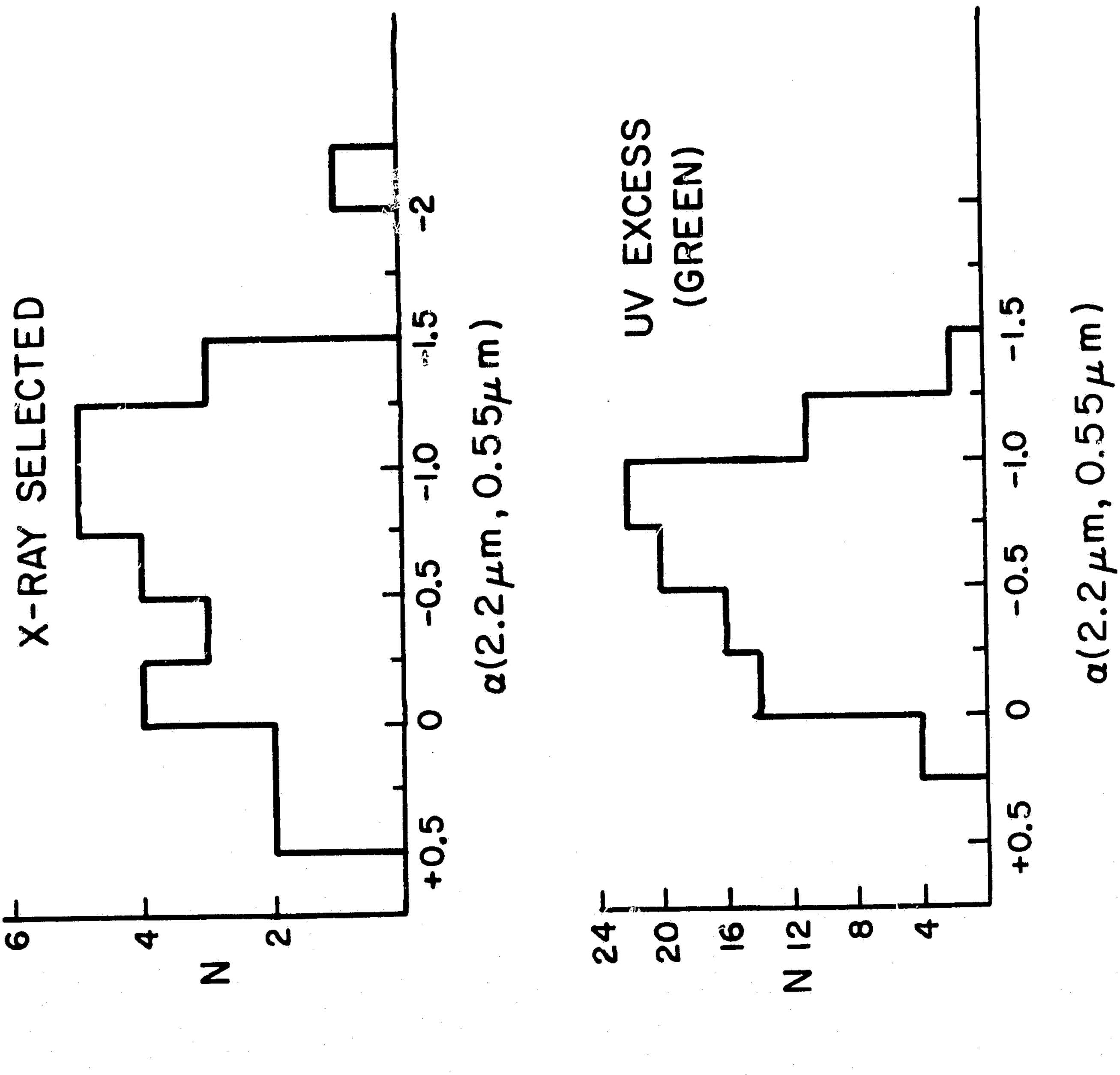
X-RAY SELECTED
N
6
4
2
+0.5
0
-0.5
-1.0
-1.5
-2
α(2.2μm, 0.55μm)
UV EXCESS
(GREEN)
N
24
20
16
12
8
4
+0.5
0
-0.5
-1.0
-1.5
α(2.2μm, 0.55μm)

Figure 1

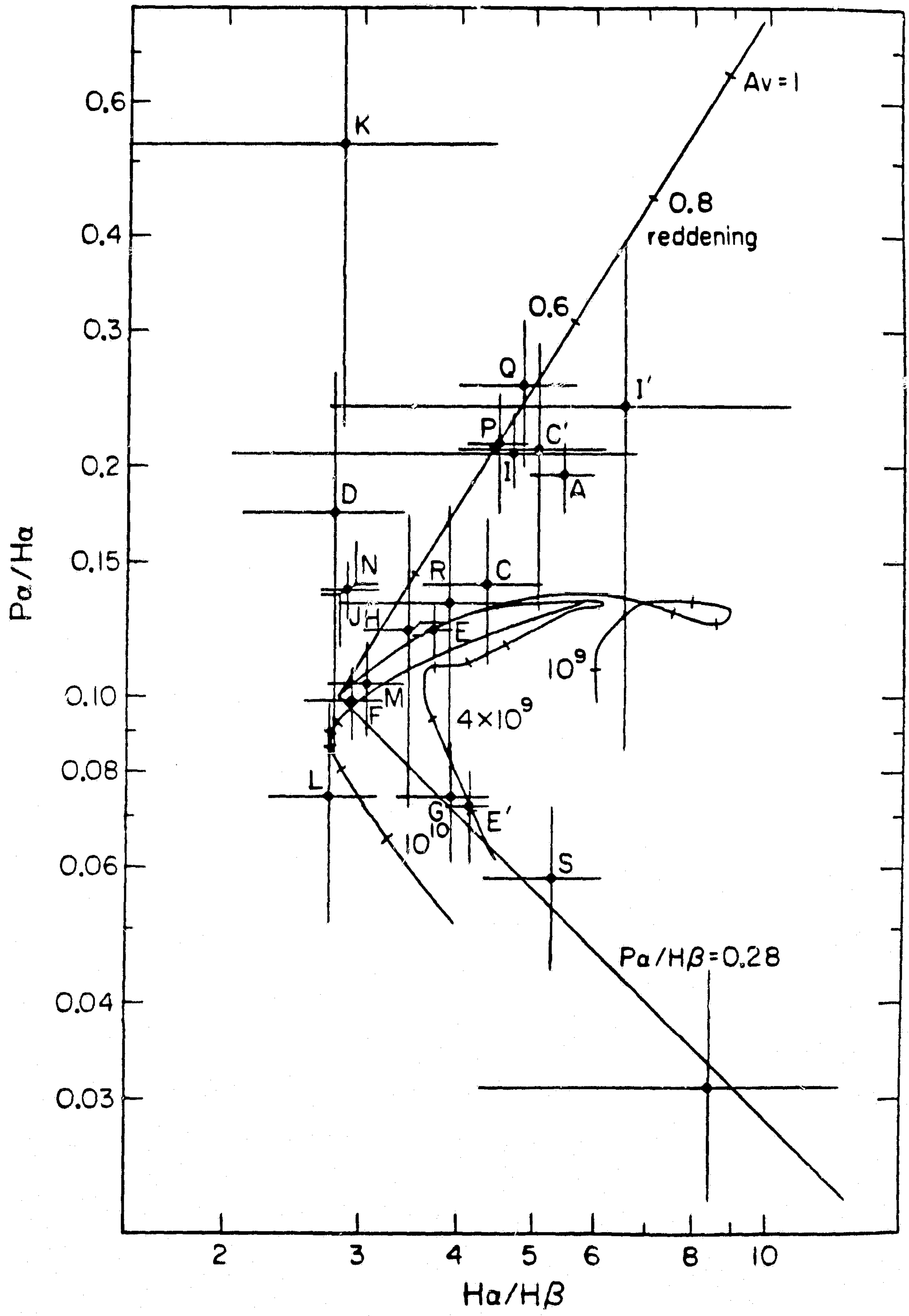
Pa/Hα
Hα/Hβ
0.6
0.4
0.3
0.2
0.15
0.10
0.08
0.06
0.04
0.03
2
3
4
5
6
8
10
Av=1
0.8
reddening
0.6
K
Q
I′
P
C′
I
A
D
N
R
C
J
H
E
10^9
M
F
4×10^9
L
G
E′
10^10
S
Pa/Hβ=0.28

Figure 2

In addition to the large scale 5 m programs, several smaller scientific programs have been carried out, largely under the auspices of graduate students.

Paschen α Line Profile in 3C273

Analysis of the Pα line profile in the low redshift quasar is making progress. This hydrogen emission line, redshifted into the 2 μm atmospheric window, was measured with ~ 800 km s^{-1} velocity resolution, using a Fabry-Perot spectrometer. The purpose of this observation was to provide a better understanding of the broad line emission regions in quasars, and particularly of the anomalous hydrogen line ratios observed in these objects. Current models explaining these line ratios fall into two groups, one attributing the observed line ratios to reddening by dust, and the other producing the emission lines in dense, optically thick clouds within the broad line region. If dust produces the anomalous line ratios, a comparison of the lines profiles of Pα, which is little affected by dust, and Hβ should yield information on the distribution of the dust within the quasar. If instead the line ratios are due to radiative transfer and optical depth effects, and the velocity of the clouds is due to systematic inflow or outflow, one might expect assymetrics between the red and blue portions of the lines, as one sees either the side of the cloud illuminated by the central energy source or not. Since Hβ is optically thick in these cloud models, while Pα is more optically thin, differences in the transfer of optically thin and thick lines within the clouds could produce differences in the amount of red/blue assymetry between Pα and Hβ.

The results of laboratory and telescope testing of the Fabry-Perot spectrometer have led to an understanding of the characteristics of the instrument, allowing a final reduction of the 3C 273 data, The final best spectrum is shown in Figure 3. A first comparison of the $P\alpha$ line profile with the $H\beta$ profile published by Boksenberg et al. (M.N.R.A.S. 172, 289, 1975) shows the two to be very similar. Work is proceeding on a more detailed comparison, and on an investigation into what predictions would be made by cloud models for the magnitude of line profile differences due to radiative transfer and optical depth effects.

X-Ray Burster Observations

During the last summer an extensive observational program searching for infrared bursts was carried out in coordination with X-ray satellite observations and infrared ground based observations from Hawaii. X-ray bursts are well known, and infrared bursts have been reported previously by several groups, but infrared bursts have never been seen simultaneously with X-ray bursts or by two infrared groups. The purpose of our measurements was both to validate the presence of infrared bursts and to learn about the relationship between infrared and X-ray bursts to understand about the physics of the bursters.

During the program, 27 nights were logged at Mt. Wilson observing the globular cluster Liller I which contains the rapid burster MXB 1730-335. Around half of these were in common with X-ray measurements. Kulkorni et al. (1979 Nature 280, 819) have reported infrared bursts from this object as have Jones et al. (1980, Nature 283, 550). During the period of our

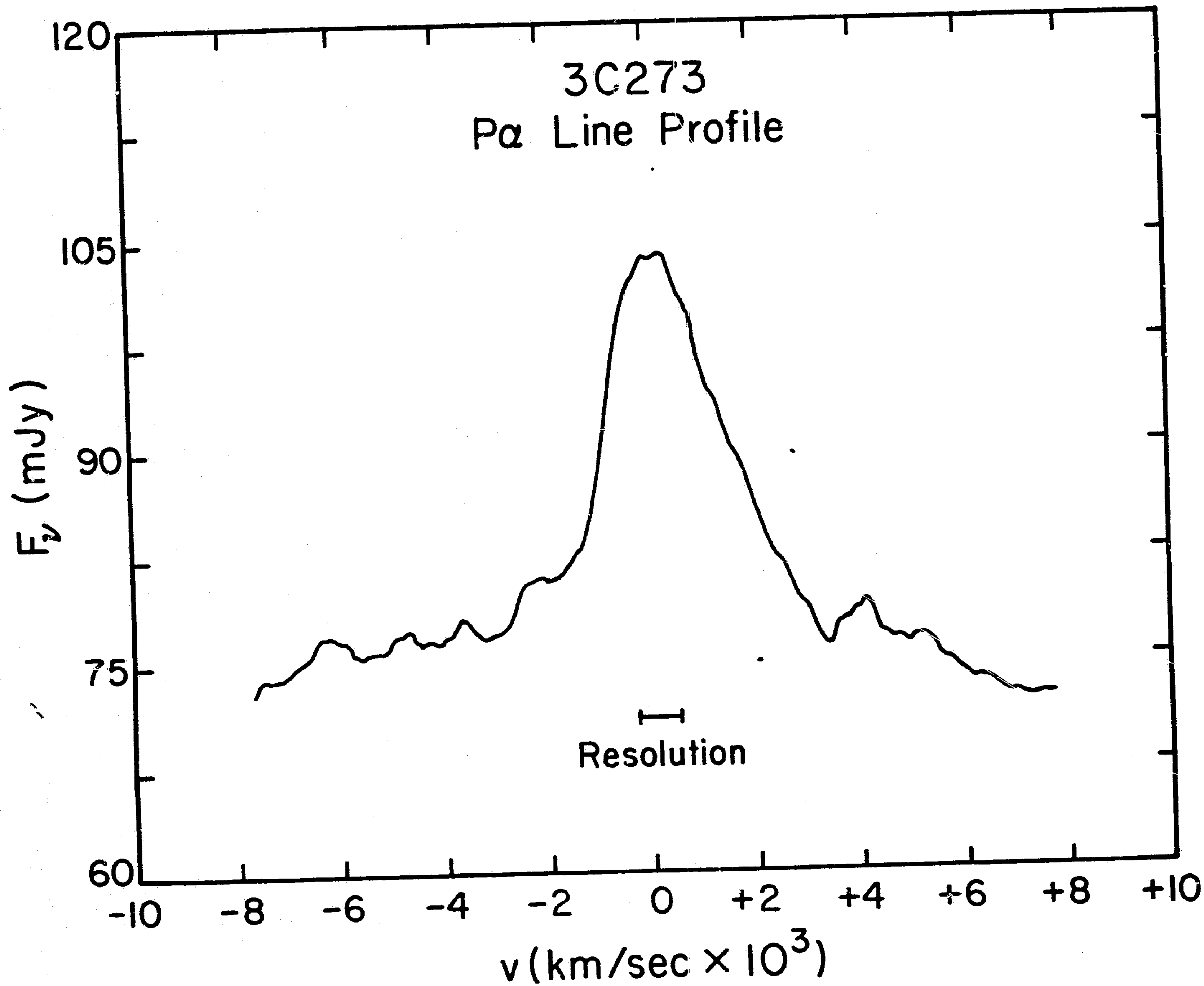
3C273
Pα Line Profile
120
105
90
75
60
F_ν (mJy)
Resolution
-10
-8
-6
-4
-2
0
+2
+4
+6
+8
+10
v (km/sec × 10^3)

Figure 3

observations, however, no bursts greater than 5×10^{-26} J m^{-2} Hz^{-1} were found, a limit well below previously reported bursts. The observations are now being prepared for publication. This program will be resumed the coming summer if unusual X-ray activity of the object is reported.

Reflection Nebula

A program has been recently begun by a graduate student, K. Sellgren, of measuring the near infrared radiation from reflection nebulae. By measuring the spatial distribution of reflected light at 1.2, 1.6, and 2.2 μm, information may be deduced about the scattering properties of dust grains in the near infrared. Theoretical predictions of the albedo and assymetry factor g are difficult to make in the near infrared due to uncertainties in the size distribution of the grains and even the appropriate values of the optical constants for typical grain materials. An observational determination of the albedo and g will be of great use, both for radiative transfer calculations which depend on these quantities, and for the information it will provide on the composition and size of the grains.

Observations at 2.2 μm of the reflection nebula NGC 7023, in collaboration with S. E. Whitcomb of Caltech, have already been completed. Observations of NGC 7023 at 1.2 and 1.6 μm are planned for this summer, and observations at 1.2, 1.6, and 2.2 μm were begun this winter on several new reflection nebulae, including NGC 2023 and NGC 2068. Preliminary results for NGC 7023 are that the albedo at

2.2 μm is probably greater than 0.7. A spectrum of the nebulosity from 1.4 to 2.4 μm, with 5% resolution, shows no spectral features, and also shows that the albedo in the near infrared rises with wavelength. This would imply that the albedo drops from visual wavelengths to 1.4 μm, then rises again to 2.4 μm. Further analysis of these observations is in progress.

One observational problem that is also being pursued is the contribution of faint field stars to the observed extended emission associated with reflection nebula. Scans at 2.2 μm have been made of several of the reflection nebulae to search for the brighter field stars, and the observed nebulosity has been corrected for their contribution. More work needs to be done to determine the number of stars below the scan detection limit. If there are significant numbers of these fainter stars, the observed value of the 2.2 μm albedo could be lowered by their contribution to the observed nebular emission.

Infrared Studies of Cataclysmic Variables

Cataclysmic variable stars are binary stars having orbital periods of several hours. They consist of a late type dwarf that fills its critical Roche surface and transfers matter to a white dwarf. The transferred matter forms a thin disc around the white dwarf; the disc lies in the orbital plane of the binary. The continuum of the disc is blue and dominates the visual spectrum of these systems.

Although the transfer of material between the components of binary stars is commonplace, the only such stars in which the light of the transferred matter dominates the luminosity of the systems are the cataclysmic systems. A study of these stars is thus of special importance in the study of the dynamics of mass transfer in binary stars.

G. Berriman, a graduate student in astronomy has been studying cataclysmic variable stars in the infrared throughout the past year. The results of this research can be summarized as follows:

i) Observations of U Gem

U Gem, an eclipsing system of period $4^h\ 10^m$, is a unique cataclysmic star in that the radiation of the red star dominates the red and infrared luminosity of the system. The properties of the red star in U Gem (hereafter called U Gem B) can thus be readily studied.

Variations arise because U Gem B is ellipsoidal in shape. This gives rise to a light curve that is doubly sinusoidal in shape. A comparison of the observed variations with those calculated for a star filling its Roche lobe provides a test of the hypothesis that U Gem B loses mass to the white dwarf by this mechanism. The infrared observations of U Gem (made on the UKIRT by I. Gatley) reveal that the infrared light curves at J, H, and K are double humped at each wavelength.

In order to model the ellipsoidal variations of red stars in cataclysmic binaries, Berriman in collaboration with Dr. S. Mochnachi (University of British Columbia) developed a computational technique to simulate the variations. A simplified model of a cataclysmic binary in which the white dwarf and the accretion disc are each regarded as point sources radiating isotropically at the surface of the white dwarf has been used. They find that the observed variation are consistent with those expected of a star inclined at 65° which fills its Roche lobe. The observations thus represent the first direct evidence of the hypothesis that the red star in a cataclysmic system fills its Roche lobe.

ii) Observations of Non-eclipsing Systems

Berriman and P. Szkody (University of Washington, Seattle) have conducted a short survey of non-eclipsing cataclysmic stars at J, H, and K with the 60-inch telescope at Mount Wilson. The following stars have been studied: KT Per, RX And, TT Ari, TZ Per, SS Aur, YZ Cnc, Z Cam, SY Cnc, EX Hya, AH Her, V603 Aql, AE Agr, SS Cyg, AB Dra, RW Tri and EM Cyg.

The purpose of the survey was to study the spectral types of the red stars which radiate the bulk of their luminosities in the infrared. A knowledge of the spectral types of the red stars permits a determination of the distances to the systems and, from this, one can estimate the luminosities of the accretion discs and, consequently, the site of mass transfer from the red star to the white dwarf: this rate depends critically on the luminosity of the disc. An estimate of the rate of mass transfer is crucial to a thorough understanding of the properties of accretion discs, for it determines the density of, and optical depth of, each element of the disc.

Berriman and Szkody found that the spectral types of red stars in the above systems differ widely, but that the infrared colors of each system can be adequately represented as the composition in wavelength of a main-sequence star and free-free emission from a plasma of emission integral $\int Ne^2\, dV = 10^{56.57}\ cm^{-3}$, ($T = 10^4$ K). The latter component of the infrared radiation most probably arises in the outer regions of the disc. The spectral types of the red stars vary from K4 (13 subclasses) in AH Her to M5 (12 subclasses) in YZ Cnc and EX Hya.

The systems also exhibit a large range of distances: AE Aqr is at 75 pc, whereas TT Ari lies at 400 pc. These results disagree with the previously determined estimates of the distances, based on the assumption that the accretion discs of cataclysmic variables have the same absolute visual magnitudes which produced distance estimates of ~ 100-200 pc to nearly all the cataclysmic stars. The estimates based on the infrared data (although accurate to ~ 30%) are more reliable because the properties of red stars are better known than those of discs. In fact, the discrepancy between ours and the previous estimates imply that discs exhibit a wide range is absolute visual luminosity.

Instrumental Development

A major portion of the effort supported by this grant in the last year has been devoted to the development of a new single element InSb photometric system for the 5 m telescope. This new system is now background photon noise limited in all near infrared photometric bands, and incorporates several features that allow for extremely versatile operation. These include:

(1) Multiple feedback resistors spanning a range of greater than 10^4 in resistance (10^8 to 2×10^{12} ohms) to permit observations over a dynamic range of $> 10^{10}$, and under conditions ranging from the very low backgrounds at 1.2 μm, to the extremely high background in the 5 μm atmospheric window.

(2) A fast (f/0.7), 23 mm diameter achromatic field lens system that allows fields of view of up to 12 arc seconds to be imaged onto a 1/4 mm InSb detector. The large field of view is required for the programs involving the studies of galaxies at large redshifts, and so that on nights of relatively poor seeing, i.e. > 4", we can continue to observe. The use of the 1/4 mm InSb detectors decreases the capacitance of the detector roughly by the area; when the limiting noise is the voltage noise of the input JFET the signal to noise ratio is inversely proportional to the capacitance at the input of the preamp. The JFET noise is minimized by heating it to a temperature of ~ 120 K.

(3) Dual remotely operated filterwheels having the capability of 20 filter slots for a wide variety of observational programs.

The performance of the system is excellent; Table 1 shows this performance, as measured on the 5 m telescope with a 6 arc second aperture, in March and April of 1981. These results represent improvements of factors of roughly 4, 3, and 2 in sensitivity over our previous system at 1.2 μm, 1.6 μm, and 2.2 μm. Much of this improvement is due to improved transmission of the optical elements, while some improvement comes from the improved noise performance of the system. From the measured noise under zero background and the measured responsivity of the system on the telescope, the detector NEP at 2 μm is 1×10^{-16} W/Hz$^{1/2}$. For constant detector quantum efficiency this would correspond to a low background NEP of 4×10^{-17} W/Hz$^{1/2}$ at 5 μm.

TABLE 1

Photometric Performance of New Caltech InSb Dewar System on 5 m Telescope

λ	1.2 μm	1.6 μm	2.2 μm
$\Delta\lambda$	0.3 μm	0.3 μm	0.4 μm
1σ noise, 1 hour integration (in magnitudes)	$21^{m}.8$	$21^{m}.4$	$20^{m}.2$
(In μJy)	2.9	2.7	5.2

B. Millimeter Wavelength Observations

The second major thrust of the Caltech infrared program involves millimeter continuum observations with the 5 meter Hale Telescope. Many of the observations are, however, coordinated with the near infrared program. One of these areas is in the monitoring of extragalactic objects. The dual millimeter/near infrared observations are providing us a base line of almost a decade to study variability in these objects.

A second example of this joint effort comes in observations of the compact radio source 1415+135 which has been studied at wavelengths from 1 μm to 1 mm using both the Palomar 5 m telescope and the NASA 3 m telescope at Mauna Kea. 1413+135 and a number of other flat spectrum radio sources have been found by Rieke, Lebofsky and Kinman (1979, Ap. J. (Letters), 232, L151) to be characterized by a very steep near-infrared to optical spectral index, $\alpha \cong -3$. Our observations have shown that 1413+135 has the following properties: 1) an energy distribution that flattens to $\alpha \cong -1.5$ at wavelengths between 2 and 10 μm; 2) a spectrum in the 1 - 2 μm region that is devoid of emission lines; 3) brightness variations on a month-to-month timescale; 4) a lack of variations in the shape of the energy distribution; 5) very strong 1 mm continuum emission roughly 1/4 as intense as that from 3C 273. The near infrared spectra are sufficient to rule out the possibility that 1413+135 is a quasar with normal Hβ + OIII emission lines at redshifts < 1.3. The overall shape of the energy distribution of 1413+135 from centimeter radio wavelengths, through the infrared and into X-rays, the lack of spectral features and the brightness variations all suggest that 1413+135 is at the extreme red end of the distribution of BL Lac objects.

The reason for the extreme redness of this source is not yet known. One possibility is simply a lack of sufficiently energetic electrons capable of producing emission at visual wavelengths. A second possibility is that dust local to 1413+135 obscures an intrinsically less steep optical spectrum. This latter alternative will be tested this spring by a measurement of 1413+135 at 100 μm using the NASA C 141 in collaboration with Dr. Paul Harvey (University of Texas). The energy absorbed by the dust in the visual has to be re-radiated at far infrared wavelengths. A limit of 1 Jy will permit one to set a sensitive limit to the amount of dust toward the source.

Dust in Quasars

It has been observed (see above) that the spectra of many quasars exhibit hydrogen emission lines with intensities considerably lower than the predictions of standard recombination theory. As an explanation for this discrepancy, it has been proposed that there is dust associated with these quasars which reddens the emission. Observations at infrared wavelengths are relevant to the hypothesis that dust is in quasars since the dust would thermally reradiate in the infrared all the power absorbed from the quasar unltraviolet continuum. Infrared measurements should be able to constrain the dust temperature or, equivalently, the distance of the dust grains from the UV continuum source.

With these ideas as motivation, one millimeter continuum observations of the high redshift quasars B2 1225+31, Ton 490, and PHL 957 were carried out by graduate student D. Ennis. The emission line spectrum of each of these quasars exhibits a $L\alpha/H\alpha$ emission line ratio in disagreement by an order of magnitude with the predictions of Case B recombination theory. Due to the improvements in detector sensitivity realized over the last few years, meaningful upper limits to the 1 mm flux density from these quasars were obtained. The upper limit to the power emitted by these quasars at an observed wavelength of one millimeter is typically half the power continuum at $L\alpha$. If it is assumed that an isothermal dust shell is reddening the quasar line and continuum emission by an amount of dust consistent with observed hydrogen line strengths, it is found that temperatures between 25 K and 50 to 95 K (depending on the quasar) are ruled out by the present data. For temperatures within this range a dust shell emitting the requisite total luminosity would produce a 1 mm flux density greater than the measured upper limit. Converting from dust temperature to distance of the dust grains from the central heating source, it is found that the average dust shell radius cannot be between 70 kpc and 1 Mpc. This result represents the first meaningful constraint on the location along the line of sight of the proposed dust reddening the radiation from quasars.

Millimeter Wavelength Observations of Galactic Sources

During the winter 1980-81 observing season, 1 mm continuum measurements were made of dust emission from a number of galactic molecular clouds using the 5 m telescope at Palomar Mountain. A high resolution map was made of the Orion Molecular Cloud (OMC-1) which, in conjunction with data from the Owens Valley 10 m telescope, shows that OMC 1 breaks up into two distinct sources, each slightly extended on a scale of 30" and separated by 75". As different molecular lines peak in different parts of OMC 1, the data obtained in the continuum where the dust emission is optically thin, help to unravel the density structure of OMC 1. Knowing the density structure will help deconvolve density effects from variations in temperature and chemical abundance in interpreting spectral line observations.

Maps with 60" resolution were also made toward a number of smaller, simpler clouds such as S140, S255, Cep A and S235. These clouds have been well studied in millimeter spectral lines. A comparison of the dust and gas column densities will allow one to monitor the gas to dust ratio within these clouds and to investigate the importance of various gas depletion mechanisms that have been proposed to explain varying molecular abundances inferred from line observations.

Millimeter Instrumental Work

The bulk of instrumental work on the millimeter program has been in the development, together with JPL, of monolithic silicon bolometers. Germanium, the standard material used for cryogenic temperature thermistors, is itself a poor absorber in the mm-region; hence the "composite" bolometers use a substrate, typically of bismuth-coated sapphire, that efficiently absorbs the radiation, and a germanium thermistor to sense the thermal energy. So far, the best composite ^{3}He bolometers have achieved an NEP of $\sim 5 \times 10^{-15}$, and at this level, the major component of the noise is thought to be junction noise from the (epoxy-bonded) substrate-thermistor interface. This noise sets an absolute limit on the performance of composite bolometers.

The fact that monolithic bolometers are not subject to this limiting junction-noise is one of several advantages they have over composites. On the other hand, by adapting a monolithic design and these fabrication techniques, we do not lose the advantage of the composite bolometer because our material is silicon, whose absorption efficiency is far higher than that of germanium, and comparable to that of bismuth coated sapphire. This absorption efficiency is independent of impurity concentration because the ionization energy of the impurities' "extra" electrons and holes is much greater than the thermal energy at LHe temperature. Hence, the task of optimizing the detectors for ^{3}He temperatures is simplified by not having to worry about degrading the absorption when the doping is altered.

In the last six months the following work on the monolithic bolometer project has been done by graduate student, E. Grossman:

(i) Tested the noise and responsivity of a 5 mm bolometer, both with and without radiation striking it. Its (optical) NEP was 4-5 x 10^{-14} W/Hz$^{-1/2}$ at 1.75 K. Note that our goal is 1 x 10^{-15} W/Hz$^{-1/2}$.

(ii) Designed and had built 20 holders for the next batch of 5 mm bolometers (which is under construction at JPL). Not only will having a separate holder for each bolometer turn the testing into a more efficient, "assembly-line" process, but also the new holders should allow for better cooling of the bolometers, which has hitherto been something of a problem.

(iii) Determined the optimal geometry and dimensions for observation-grade bolometers of this type. Though still somewhat tentative, the plan for batches following the one presently being built calls for square detectors scaled down from 5 mm to 1.25 mm on a side, and for milling down the thickness of the bolometers and the cross-section of their support legs after the photolithography process is complete, to empirically determined optima.

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