INFRARED STUDIES OF THE STELLAR CONTENT IN EXTRAGALACTIC SYSTEMS

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ABSTRACT

Normal galaxies emit most of their radiation longward of one micron, and many problems related to our understanding of galaxy formation and evolution can be fruitfully addressed with measurements at near-infrared wavelengths. Such problems include the make-up of the red stellar population, the star formation rate, the initial mass function, metallicity effects, and mass-to-light ratio. How these various quantities depend on morphological type, on total mass (or absolute magnitude), on radial position, and on environment is also of great interest. In this review recent infrared observations of extragalactic stars, star clusters, and galaxies having important bearing on these questions are discussed. Particular emphasis is placed on new evidence for the presence of a finite intermediate age population in early-type systems. This evidence comes from observations of intermediate age stars in many Magellanic Cloud globular clusters, observations of such stars in at least one nearby dwarf spheroidal (Fornax), the difficulties of fitting theoretical isochrone models to the red V-K colors of E and S0 galaxies, and the differences in the infrared color-magnitude relations for the Virgo and Coma clusters.

> "It is not very bright to measure a blue magnitude for a red object."
> -- Vera Rubin

I. INTRODUCTION

Knowledge about the stellar content in other galaxies is essential for understanding the processes underlying galaxy formation, structure, and evolution. Because most galaxies emit the bulk of their radiation in the near infrared, measurements at these wavelengths provide a uniquely important view of the universe. The development of highly

C. G. Wynn-Williams and D. P. Cruikshank (eds.), Infrared Astronomy, 297–316.

sensitive InSb detector systems within the last five years has enabled a number of detailed infrared stellar-content studies to be undertaken, and as we shall see, unexpected and intriguing results have often emerged.

This article will mostly be concerned with observations conducted in the one to three micron region of objects whose luminosities are contributed mainly by direct stellar radiation. The emphasis will be placed on newer results, which in many cases have yet to appear in print. For longer wavelength studies, and a more comprehensive listing of the published literature, the reader is referred to the recent review article of Rieke and Lebofsky (1979). Note that the topic of active star formation in spiral galaxy nuclei will scarcely be touched upon here, as the subject is discussed in another article in this volume by G. Rieke. Also, I have not attempted to cover the entire field of stellar populations, but rather, to indicate those areas where the infrared can make and has made a particularly worthwhile and interesting impact.

The plan is to first discuss IR observations of individual stars and star clusters and what they have revealed about the stellar content in nearby galaxies (including our own). Next, attempts to synthesize the light of E and S0 galaxies, systems which are thought to have ceased all star formation long ago, will be summarized. Emphasis will be placed on metallicity effects and the nature of the coolest stellar component. Finally, studies involving spiral galaxies will be examined.

Certain photometric observations have proven especially useful in analyzing composite red stellar content. These include broad band measurements at J (1.2 microns), H (1.6 microns), K (2.2 microns), and L (3.5 microns); and narrow band measurements of 2.3 micron CO and 1.9 micron H_2O indices. The CO feature is a sensitive measure of luminosity in late-type stars, and is well-suited for determining the giant-to-dwarf ratio; while H_2O absorption provides information about the very coolest stars present (see Baldwin, Frogel and Persson 1973). Further uses for the IR data will be developed as we proceed.

II. STARS

IIa. Relevant Galactic Work

In order to construct stellar synthesis models of the integrated light from extra-galactic systems, it is desirable to have a library of calibrating stars having as wide a range as possible in temperature, luminosity, and metallicity [M/H]. Calibrations of the various IR colors and band strengths of concern here as a function of spectral type and luminosity are given by Johnson (1966a); Lee (1970); Persson, Aaronson and Frogel (1977); Frogel et al. (1978); Aaronson, Frogel and Persson (1978b); and Ridgway et al. (1980). The main drawback of these compilations is that they are primarily applicable to stars believed to be near or perhaps a bit below solar [M/H] values.

https://doi.org/10.1017/S0074180900075288 Published online by Cambridge University Press

Some progress in establishing an empirical library having wider metallicity coverage is being made through the study of giant stars in galactic clusters (Cohen, Frogel and Persson 1978; Pilachowski 1978; Frogel, Persson and Cohen 1979; Persson et al. 1980c). These authors measure JHK magnitudes and narrow-band CO and H_2O indices for cluster giants reaching typically 3 mag below the giant branch tips. An accurate bolometric magnitude (M_{bol}) and effective temperature (T_{eff}) can be calculated from the JHK data, leading to reliable placement of the cluster stars on the physical HR diagram for comparison with theory. The model atmosphere calculations in Cohen et al. (1978) suggest that both J-K and V-K colors can be used to derive proper effective temperatures for metal-poor giants, independent of gravity or metallicity. The models, however, do not include molecules, which may partially explain their discrepancy with recent empirical evidence suggesting that a metallicity dependence in the (V-K, T_{eff}) relation does exist for the coolest stars (Mould and Aaronson 1980; and see below).

An important result from this series of papers, and a point I will come back to several times again, concerns the good agreement between the empirical giant branches and the theoretical models of Rood (1972) and Sweigart and Gross (1978). In particular, it appears that in the HR diagram, asymptotic giant branch (AGB) stars in metal poor galactic globulars do not rise above the first giant branch tip, a limit believed to be imposed from mass loss.

One other interesting result has developed from the cluster studies. At the metal poor and rich ends, both the CO strength and the effective temperature of the giant branch correlate well with other [M/H] estimators. However, there is some breakdown of this correlation with the intermediate-metallicity clusters. Pilachowski (1978) has pointed out that for these clusters the CO index correlates not with [M/H] but with horizontal branch morphology. The infrared observations thus lend support to the idea that variation in the [CNO/Fe] ratio relates to the well-known second parameter problem in galactic globulars.

IIb. Stars in Nearby Galaxies

The galaxies in the Local Group are sufficiently close to be easily resolved into stars. The Magellanic Clouds provide a particularly happy hunting ground for infrared studies of the cool stellar content, as there is available a large sample of stars with little reddening all at the same distance. Glass (1979) has published JHKL photometry of late-type supergiants in both the LMC and SMC. He finds that the bolometric magnitudes of these stars decrease with advancing spectral type, in apparent contrast to such stars in our own galaxies. Glass also finds that for the brightest supergiants, types M0-M1, $|M_{bol}$ (LMC) $|>|$ M_{bol} (SMC) $|>|$ M_{bol} (Milky Way)$|$. However, this last result may be subject to some serious selection effects.

https://doi.org/10.1017/S0074180900075288 Published online by Cambridge University Press

Humphreys and Warner (1978) have detected several luminous blue variables in both M31 and M33 at K. These stars appear similar to Eta Carinae-type and S-Doradus type variables in the Milky Way and LMC.

Mould and Aaronson (1979, 1980) have spectroscopically identified numerous carbon and M stars at the tip of the giant branch in a number of red globulars in the Magellanic Clouds. JHK photometry for many of these stars has been obtained by Frogel, Persson and Cohen (1980a) and Mould and Aaronson (1980); the IR data is essential for accurately calculating the bolometric luminosities of these very cool giants.

The M_{bol}'s of the Cloud cluster carbon stars are found to range between -4.5 and -5.5 mag, which places them 1-2 magnitudes above the giant branch tip of galactic globulars. Mould and Aaronson (1979, 1980) have argued that these are AGB stars which can only be produced by clusters of intermediate age (e.g. 1 - 8 billion years old). These authors have developed a relation between the age of a cluster and the luminosity at the top of the AGB. Physically, such a relation exists because more massive (i.e. younger) stars have larger envelopes and can attain higher luminosities before attrition of the envelope due to mass loss. From the IR data, Mould and Aaronson have derived independent age estimates for the clusters in their sample, and find strong hints of a cluster age-metallicity correlation, which is expected if chemical enrichment has occurred over the cluster formation period. In the Clouds the presence of both young globulars and old ones resembling those in the Galaxy was known for years. The identification of intermediate age clusters suggests that the birth of Cloud globulars has been a continuing process, in marked contrast to the situation in the Milky Way.

The interpretation that carbon stars imply (relative) youth in metal-poor populations provides a natural explanation for the remarkable observations of Blanco, Blanco and McCarthy (1978). These authors find that in the central bulge of the galaxy, M stars outnumber carbon stars 300 to 1; while in the field of the LMC carbon stars outnumber M stars 2 to 1; and in the SMC they outnumber M stars 50 to 1. Thus, the predominance of oxygen-rich stars in the Milky Way is consistent with the presence of an old enriched stellar content; while the Clouds would appear to have a large intermediate-age, metal-poor population, with the absence of M stars in the SMC reflecting a lower [M/H] than is found in the LMC. This view agrees well with Butcher's (1977) finding from an analysis of the LMC luminosity function that a large LMC intermediate-age field population is indeed present.

There are several further aspects of the Cloud cluster IR data worth mentioning. First, the JHK colors of the SMC cluster carbon stars are in the mean bluer than those in the LMC, which supports the view that the SMC has lower mean metallicity. Second, the non-carbon cluster stars scatter nicely about the mean galactic field (J-H, H-K) two-color relation, and yet depart significantly from the field (J-K, V-K) relation. The departure is in the sense expected if V-K is metallicity dependent, and yet surprisingly large. The upshot is that values of T_{eff} calculated from J-K are significantly less (typically 200K) than values calculated from V-K. Since J-K appears less sensitive to changes in [M/H] than V-K, a (J-K, T_{eff}) relation seems preferable for use with cool, metal-poor stars. Using a T_{eff} calibration based on model atmospheres, Frogel et al. (1980a) have argued that the location in the HR diagram of M-type cluster stars was inconsistent with theoretical isochrones if the stars are of intermediate age. This problem is resolved when a (J-K, T_{eff}) scale tied to the stellar diameter work of Ridgway et al. (1980) is used instead.

Aaronson and Mould (1980) have observed a number of the very red stars found by Demers and Kunkel (1980) in the Fornax dwarf spheroidal galaxy, both spectroscopically and in the infrared. These stars appear very similar in nature to the Cloud cluster carbon stars. Most significantly, the M_{bol}'s calculated from the JHK photometry place these stars $\sim$ 2 magnitudes above the first giant branch tips of galactic clusters. In analogy with the Clouds, it would appear that Fornax also contains an intermediate-age population. By comparing the fractional carbon star light in Fornax and the Cloud globulars, Aaronson and Mould estimate that 20% of Fornax is of intermediate age. These authors have suggested a correlation between age spread in dwarf spheroidals and their total masses, with Fornax, the most massive dwarf spheroidal, retaining longest the gas necessary for continued star formation. Small numbers of carbon stars have now also been identified in Sculptor, the next most massive spheroidal known. IR photometry of those stars is needed to confirm their similarity with the Fornax and Cloud carbon stars.

In the next few years we can expect to see an increasing number of papers related to IR measurements of extragalactic stars, which leads me to an area where the infrared could prove particularly valuable -- the determination of the distance scale. The two most powerful stellar distance indicators may be Cepheids, and the brightest M supergiants. The latter appear to attain a remarkably constant maximum visual luminosity in galaxies with widely varying absolute magnitude (Humphreys 1980). However, two familiar problems plague the use of these indicators -- reddening and metallicity. For instance, some of the galactic calibrating Cephids have E(B-V) as large as 1.5 mag! Much of the well-known dispute between Sandage and Tammann,and de Vaucouleurs rests with how one models the correction for galactic absorption. Reddening in other galaxies may also be important. Work by Humphreys (1980) suggests that the brightest supergiants are reddened in their parent galaxies by typically 1/2 magnitude in A_V. This effect has not been previously accounted for, but that it exists should not be too surprising when one considers that the brightest supergiants are often found near dusty, active regions of star formation. An example of a possible metallicity problem is the different (B-V, period) relations for galactic and LMC Cepheids, a result attributed to differences in [M/H] and requiring a somewhat uncertain correction (e.g. Martin, Warren and Feast 1979). Furthermore, very little is understood about how changes in [M/H] might affect the calibration of the M supergiants.

https://doi.org/10.1017/S0074180900075288 Published online by Cambridge University Press

Infrared observations of Cepheids and M supergiants have the potential for completely circumventing the problem with reddening, and perhaps alleviating any problems with metallicity as well. With present IR equipment, extra-galactic Cepheids are not measurable to very great distances, perhaps just barely to M31. The M supergiants are another story. These are well within the capability of detection in galaxies as far away as M101, at about 6.5 Mpc. Crowding problems are not as severe as one might think if the chopping is done against a reasonably uniform background since the objects are going to be much redder than anything else around. How rewarding IR studies of these distance indicators will actually be is unclear, and will depend on such factors as whether or not the M supergiants evolve in constant M_{bol}, as opposed to constant M_V. Nevertheless, the potential rewards are sufficiently great that I believe the effort involved is worth making.

III. STAR CLUSTERS

Infrared photometry of star clusters provides a powerful diagnostic tool in constructing stellar synthesis models for the integrated light of galaxies. Because clusters are coeval and of uniform metallicity, they enable a straightforward empirical check to be made against theoretical models of varying [M/H] and age. IR measurements have now been conducted for clusters in the Galaxy (Aaronson et al. 1978a, hereafter ACMM), in the Magellanic Clouds (Persson et al. 1980a), in Fornax (Aaronson and Mould 1980), and in M31 (Frogel, Persson and Cohen 1980b). Each of these studies will be briefly discussed.

ACMM measured JHK magnitudes and CO and H_2O indices for about 40 galactic globulars. The V-K, J-K, and CO indices were found to correlate well with [M/H]. This result was not unexpected, since the integrated colors should become redder with increasing [M/H] owing to greater line blanketing, shifting of the horizontal branch, and cooling of the giant branch. Because V-K colors are particularly sensitive to the last effect, it was hoped that they would provide a more accurate measure of [M/H] than U-V. In fact only a marginally better correlation was seen for V-K than for U-V, but the errors in V-K are considerably larger owing to both instrumental and reddening uncertainties.

Persson et al. (1980a) have obtained IR data for some 84 clusters in the LMC and SMC. Included in this sample are open clusters, blue populous clusters, and red (including many intermediate age) globulars. An important result of this work is the degree to which carbon stars dominate the integrated light in some of the intermediate age clusters. NGC 2209 provides a particularly striking case. This cluster has a well determined age from the main sequence turnoff of 0.8 billion years (Gascoigne et al. 1976), and a comparatively high value of -0.5 for [M/H] (Gustafsson, Bell and Hejlesen 1976). Its U-V color is $\sim$ 0.9 (Bernard 1975), which is about 0.3 mag bluer than what one might expect for a galactic globular of comparable metallicity. However, the V-K color of this object is about 3.6 $\pm$ 0.2 (the large error being due to a significant mismatch in the optical and IR aperture sizes). This V-K color is a magnitude redder than comparable galactic globulars, and is in fact as red as the reddest early-type galaxies. It turns out the extraordinary colors of this object may be due to the presence of a single carbon star in the beam!

The IR Cloud cluster data will provide a much needed empirical constraint on future synthesis models of active star-forming galaxies. The only published models of this kind with IR colors are those of Struck-Marcell and Tinsley (1978). These models do not include objects with anything like the colors of NGC 2209, nor do they successfully fit the cloud open cluster data, suggesting a revision is required in the supergiant evolutionary tracks.

To determine whether Fornax might also contain intermediate age globulars, Aaronson and Mould (1980) measured JHK colors for four of this galaxy's clusters. One of these objects, Hodge 2, has quite red H-K colors and probably contains carbon stars.

Frogel et al. (1980b) have obtained infrared data for some 40 globular clusters in M31. The various IR colors are found to be tightly correlated with optical colors and line strengths. The spectral flux from 0.3 to 2 microns thus appears uniquely defined by a one parameter relation with [M/H]. Frogel et al. derive metallicities for the M31 from V-K colors; these authors agree with the earlier conclusion of van den Bergh (1969) that M31 globulars are weighted toward larger [M/H] values, but do not find that the upper bound of [M/H] in M31 is any greater. It should be noted that the absolute [M/H] calibrations presented by ACMM and Frogel et al. (1980b) are called into question by recent evidence from Pilachowski, Canterna and Wallerstein (1980) and Cohen (1980) that the metal rich globulars 47 Tuc and M71, thought to have [Fe/H] $\sim$ -0.4, are actually metal poor, with [Fe/H] $\sim$ -1.1. However, the relative ranking in [M/H] from IR colors should still be basically correct.

IV. GALAXIES

In this section we will see how the advent of modern infrared measurements has affected present day understanding of the composite light from galaxies.

IVa. Early-Type Galaxies

An extensive survey of early-type (E and S0) infrared galaxy colors was undertaken by Frogel et al. (1978) and Aaronson et al. (1978b). JHK colors were measured for some 50 nearby ellipticals, along with CO and H_2O band strengths. (Additional JHK data is also in Persson, Frogel and Aaronson 1979). These data placed some stringent contraints on the stellar synthesis models of Tinsley and Gunn (1976) and O'Connell (1976), favoring those models having giant-star dominated populations with small

https://doi.org/10.1017/S0074180900075288 Published online by Cambridge University Press

mass-to-light ratios ($M/L \sim 5$). Models having a slope in the initial mass function (IMF) of $x \lesssim 1$ (following Tinsley's 1972 notation) agreed best with the data. In addition, the strength of the H_2O index suggested the presence of a stellar component at least as late as M5. An important implication of all this was that a large evolutionary correction ($\Delta q_0 > 1$) was required in cosmological tests of the deceleration parameter (Tinsley 1972).

A further finding of Frogel et al. (1978) was that the V-K and J-K colors tended to redden with decreasing aperture size and increasing luminosity, trends that also occur with optical colors and line indices. Infrared color changes with radial position have also been reported by Strom et al. (1976, 1978). Strom et al. (1978) argued that the qualitative similarity in the ratio of optical to IR color changes seen between and within galaxies supported a similar causal origin for the color-aperture and color-magnitude effects. On the other hand, Frogel et al. (1978) reported marginal evidence for a difference in the ratio of color changes among and within galaxies, the effect existing largely in the J-K color. Curiously, such a result was not obtained by Aaronson (1977) for early-type spirals, which are largely bulge dominated. I believe the effect found by Frogel et al. arises in part from instrumental difficulties associated with measurements in the J band; in any event, the question of relative color changes is worth further pursuit.

It is probably safe to say that the color variations discussed above are today almost universally accepted as arising from changes in metallicity. In fact Faber (1973) has argued that for E galaxies the color-luminosity effect can be ascribed to a one parameter relation with [M/H], although the existence of a second parameter, perhaps related to axial ratio, has recently been proposed by Terlevich et al. 1980.

Tinsley (1978) and ACMM attempted to calibrate the integrated optical and IR colors of early-type galaxies as a function of [M/H]. Both the details of these models and the results differed in a number of important respects. In particular, Tinsley found that bright ellipticals were somewhat metal poor ($[M/H] \sim -0.3$) and that $x < 1$; whereas ACMM concluded the E galaxies were metal rich ($0 \lesssim [M/H] \lesssim 0.3$) and that x could be larger than 1 and perhaps as large as 2. The reason for these differences has sometimes been misunderstood. The principle cause is traced back to the fact that the giant branch used by ACMM is based entirely on the Ciardullo and Demarque (1977) theoretical isochrones, with AGB stars not rising in M_{bol} above the first giant branch tip, in agreement with the empirical evidence seen in galactic globulars; whereas Tinsley's giant branch is based on a semiempirical luminosity function for old disk stars and contains objects with M_{bol}'s up to -5.5 mag , that is, two magnitudes above the first giant branch tip.

A revision of the ACMM models has been calculated by Frogel et al. (1980b), incorporating the new temperature scale of Ridgway et al. (1980) and a new globular [M/H] scale at the metal rich end (see § III above).

These models are somewhat redder at a given [M/H] than the ACMM models. The models which best fit the early-type galaxies have solar metallicity and x = 1.35 (the Salpeter value).

ACMM and Frogel et al. (1980b) show that bright early-type galaxies have redder broad band colors and stronger narrow band indices than either galactic or M31 globulars. In a (U-V, V-K) color diagram the galaxy sequence is considerably displaced from the cluster sequence -- at fixed U-V galaxies are about 0.3 mag redder in V-K, and no combination of clusters can reproduce the galaxy colors.

Both the ACMM and Frogel et al. models adequately fit the cluster data, and the galaxy infrared color-color and color-band strength relations. However, there is a serious problem with both sets of models in that they do not at all match the UVK colors of E galaxies. (This problem is present in Tinsley's 1978 models, but apparently to a much lesser extent.)

Something appears to be missing in both the ACMM and Frogel et al. models which is present in early-type galaxies. The precise nature of this missing component rests with whether the problem lies in U-V or V-K; that is, whether a hot or cool luminous component needs accounting for. This is in fact not an obvious choice. A hot ultraviolet component has been detected in a number of bulge-dominated galaxies with IUE, but its size is not nearly enough to account for the discrepancy here (cf. Wu et al. 1980). Frogel et al. (1980b) concluded the problem exists with V-K, and I concur with this point of view. Before considering the nature of the missing cool component, further evidence for its existence will be discussed.

Aaronson, Persson and Frogel (1980) have carefully examined the U-K and V-K color-magnitude (CM) relations in the Virgo and Coma clusters. The original motivation for this study was the hope that the CM method of determining relative cluster distance moduli might be improved, since the size of the effect is doubled in going from a U-V to a U-K color. Whether this hope can be realized rests with the answer to two questions. First, for a given cluster sample is the scatter in the U-K CM relation smaller than in the U-V CM relation? Second, is the U-K CM relation universal? This latter point is a necessary requirement if we are to interpret the apparent magnitude difference between two clusters at some fixed color as being in reality an accurate reflection of relative distance modulus.

It turns out the answer to the first question is that the scatter in magnitude is the same when U-K is used instead of U-V. Thus no advantage is gained by going to the IR. This result provides strong support for the conclusion reached by Visvanathan and Sandage (1977) that the scatter in the CM effect is dominated not by observational error, but by true cosmic variation.

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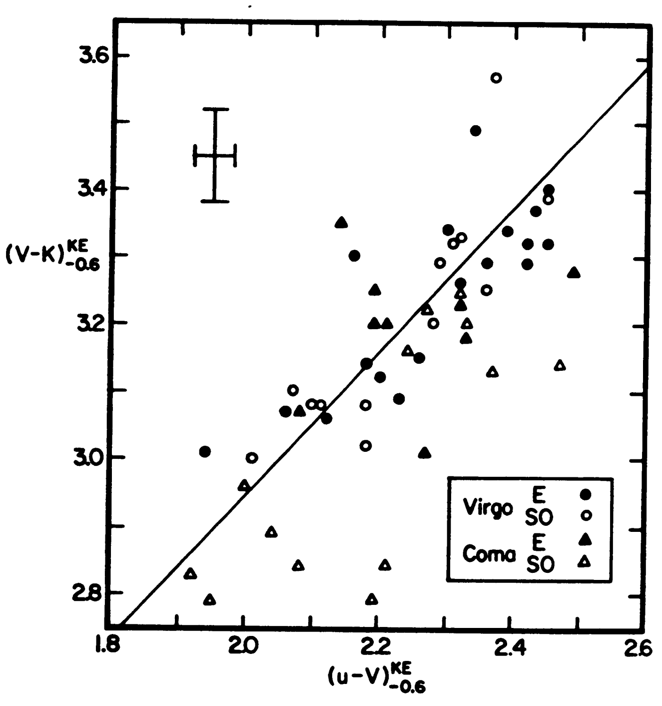

Figure 1. A (V-K, u-V) two-color diagram for early-type galaxies in the Virgo and Coma clusters. The data have been corrected for reddening, redshift, and aperture effect. Most Coma objects, especially the SO's, lie to the right of the least-squares line, which has been fit to the Virgo data only.

The answer to the second question is unexpected -- the (U-K, V) CM relation does not appear to have a universal form. To see this, first consider Figure 1, which shows a plot of U-V against V-K for galaxies in the Virgo and Coma clusters. (The notation in the Figure follows that of Visvanathan and Sandage 1977.) It is clearly seen in Figure 1 that the distribution of points in the two clusters does not overlap -- the majority of Coma points lie to the right of the least squares line fit to just the Virgo data. This shift could result from a color change in either U-V and/or V-K, but the following argument suggests that the shift is in fact primarily in V-K: the relative distance moduli between Coma and Virgo predicted from the ratio of redshifts is 4.17 mag (see Aaronson _et al_. 1980). Now the infall velocity toward Virgo is at present a controversial subject, but current estimates range between 200 - 500 km sec^{-1}. This leads to a predicted relative magnitude shift at fixed color of Δm = 3.50 - 3.85 mag. From the U-K CM relation

Aaronson *et al*. find a difference of $\Delta m = 3.00 \pm 0.2$ mag; the infall velocity implied from this magnitude difference seems unquestionally too large. (The author does not understand the value of 3.66 ± 0.35 mag quoted by Tammann, Sandage and Yahil 1979, which is based on these same data.) However, when separate solutions are made for U-V and V-K colors, the results found are $\Delta m = 3.49 \pm 0.2$ mag and 2.56 ± 0.3 mag, respectively. In other words, the value of Δm calculated from U-V colors is close to the expected range, while the value found from V-K colors is considerably too small. At fixed U-V color (and absolute magnitude), galaxies in Coma appear to be 10% bluer in V-K than those in Virgo, and it would seem that a second parameter is required to fully describe the CM effect. (Whether this parameter is related to the one proposed by Terlevich *et al*. 1980 and mentioned above is presently unclear.)

What might the nature of this second parameter be? First, note that in Figure 1 the color-shift effect is especially pronounced for the S0 galaxies. Second, when the UVK colors of nearby field galaxies are plotted, they fall along a relation similar to Virgo galaxies, with the brighter field S0's appearing to have somewhat *redder* V-K colors than those in Virgo. Thus, Coma galaxies (especially S0's) tend to be missing a cool stellar component found in Virgo and field galaxies and perhaps enhanced in field S0's, assuming dust effects can be neglected. Is this cool component related to the missing cool component discussed earlier in regard to the isochrone models? I suspect the answer is yes.

Let us turn to the question of what these cool stars might be. One possibility is red dwarfs, but this would appear to be ruled out by the observed CO indices. A second possibility relates to the idea of a very metal rich population missing from the isochrone models and the Coma galaxies. Perhaps galaxies in the dense regions of Coma were stripped of their gas before being able to form such a population.

A third possibility is that both the isochrone models and the Coma galaxies are missing giant stars which populate the HR diagram 1 to 2 magnitudes above the first giant branch tip. Recall that it is the presence of such stars in Tinsley's (1978) models which yield better agreement with the UVK colors. By analogy with the Magellanic Cloud work discussed earlier, we are led to the implication that early-type galaxies contain a finite population of intermediate age stars. In this regard, it is interesting that evidence of a significant intermediate age population has been presented for M32 by O'Connell (1980) and (as discussed earlier) for Fornax by Aaronson and Mould (1980). Stripping of Coma cluster galaxies at an early time could again account for the differences seen there.

Conclusive evidence for an intermediate age population in early-type galaxies would have a profound impact on the conventional wisdom related to these systems, so it is important to consider whether stars 2 magnitudes above the first giant branch tip necessarily implies youth.

The answer may depend on whether the mass loss rate is independent of [M/H]. The absence of high luminosity AGB stars from galactic globulars certainly argues that the mass loss rate does not change much from an [M/H] of -2 to -1 (although Frogel et al. 1980a do show that the reddest variables in 47 Tuc rise $\sim$ 0.4 mag above the first giant branch tip, so perhaps a small [M/H] dependence is present). If we are to avoid the notion of intermediate age stars, it would seem that the mass loss rate in one solar mass objects with [M/H] $\sim$ 0 must be significantly less than in metal-poor stars.

A number of arguments suggest that the intermediate age stars being considered here are not likely to be carbon stars, as in the Clouds. First, there is the circumstantial evidence provided by the absence of these stars in the Milky Way's bulge (Blanco et al. 1978). Second, the observed CO and H_2O indices appear incompatible with the presence of carbon stars (Aaronson et al. 1978b), as do K-L measurements (Aaronson 1978b; Frogel, unpublished data). Finally, FTS spectra discussed below show no evidence for the 1.8 micron Ballick-Ramsay bands, a strong carbon star discriminant.

A key debate occupying much of the astronomical literature in recent times has concerned the evolutionary status of SO galaxies. One point of view (e.g. Sandage and Visvanathan 1978) is that environmental effects do not play a significant role in determining the formation and evolution of SO's. The opposite viewpoint (see Strom and Strom 1978) is that some (if not most) SO's are, in effect, stripped spirals. To support the former view, Sandage and Visvanathan cite the similar UBV color distribution for E and SO galaxies both inside and outside clusters. However, we have seen evidence here that the UVK color distribution does depend on cluster environment. It is clearly of importance to confirm this effect with further observations of galaxies in clusters of varying richness and density.

Before leaving this thorny subject let me note that considerable progress in understanding the stellar content of other early-type systems may come about through several studies currently underway of stars in the Baade's window region. Coordinated optical and IR measurements will hopefully enable the luminosity and metallicity distribution of these stars to be determined, providing our best opportunity of studying a galaxy's bulge component in detail.

Finally, I should mention that several groups are actively pursuing near-infrared measurements of high-z ellipticals. Theoretical predictions based on single-burst models suggest that such measurements may have considerable advantage over optical data in constructing the classic Hubble diagram, in that evolutionary effects should be less important (Spinrad and Bruzual 1980). This will clearly not be the case if residual star formation in ellipticals has continued for a significant length of time, as suggested above. It is thus of great interest that Lebofsky (1980) may be finding significant H-K color evolution at redshifts too small to show such evolution in the single burst models.

https://doi.org/10.1017/S0074180900075288 Published online by Cambridge University Press

IVb. Spiral Galaxies

In a seminal study, Johnson (1966b) found that the red stellar component in galaxies having a wide range in type was rather similar, that most of the longer wavelength radiation came from K and M giants, and that some very cool stars are present. More recently, Aaronson (1977, 1978a) has measured integrated JHK colors and CO and H_2O indices for a large number ($\sim$ 90) nearby bright spiral galaxies. To first order, these data confirm Johnson's (1966b) conclusion that the underlying red population in spirals and ellipticals is the same: the JHK colors show little dependence on morphology; only for type Im is a significant "blueing" of the colors seen. Further, the narrow-band indices hardly vary through types E to Sbc. However, for types Sc and later there is evidence the CO index decreases, going from a mean value of 0.16 mag for type Sbc to 0.11 mag for type Im. This result seems to contradict star formation models of the type calculated by Huchra (1977) and Struck-Marcell and Tinsley (1978), which suggest an increasing dominance of supergiants in late-type spirals which would drive the CO index up. I believe the observed downturn in CO index is real and reflects the lower metallicity late-type spirals are thought to have, but the sample is small and additional systems should be measured to confirm the effect.

The UVK colors of spirals exhibit a rough segregation with type that is analogous to the trend seen with UBV colors. This spiral sequence exhibits a clear separation from the elliptical galaxy-globular cluster sequence in that, for the spirals, V-K changes as a much slower function of U-V. This effect is simply accounted for by the difference between a metallicity change, which immediately affects the V-K color, and a population change produced by adding young blue stars to old red ones, which has little effect on the V-K color.

The V-K and J-K colors of spirals become redder with decreasing aperture size, as in E and S0 galaxies. It is interesting to compare the relative size of the U-V to V-K color change as a function of type. For the Sab galaxies studied by Aaronson the changes in the two colors are comparable, both becoming redder by about 0.13 mag in the interval -0.3 to -1.3 in log A/D(0) (following the notation of de Vaucouleurs, de Vaucouleurs, and Corwin 1976). For Sb and Sbc galaxies the color change over this same interval is 0.32 mag and 0.36 mag for U-V, but only 0.13 mag and 0.22 mag for V-K, respectively. The color changes seen in V-K thus appear to lag behind those found in U-V. A similar sort of effect is seen when optical and infrared growth curves are compared -- for a given spiral type the IR growth curve is shallower than the optical one. Both of these results can be understood as the composite effect of superimposing a young population with a blue radial gradient on an old red population which is perhaps more spherically symmetric. For spiral galaxies of type Sa - Sb the IR colors appear in fact to be largely bulge dominated, and they very much support the notion that the stellar content in the bulges of E, S0, and spiral galaxies is the same. In particular, if the V-K color-aperture relation is interpreted as indicating a metallicity change, then it seems that in the mean the bulges of early-type spirals have the same composition gradients as are found in E and S0's, which suggests that bulge dominated galaxies have similar star formation and chemical enrichment histories in their inner regions. The last qualification is important, as Strom and Strom (1978) offer evidence that the halo color gradients found in E and S0 galaxies differ.

Aaronson (1977) also looked for a V-K color-magnitude effect in his spiral galaxy data, but found none. However, the sample was rather ill-suited for this purpose owing to the rather narrow magnitude coverage. Visvanathan and Griersmith (1977) have identified a significant U-V color magnitude relation for Sa spirals in Virgo and 11 other groups, and infrared observations of this sample would be of interest.

While a number of synthesis models for spiral galaxies have been published, two considerations make detailed comparison between the models and the IR data difficult. First, M giant stars are often either ignored completely or treated in a very superficial fashion as, for instance, by lumping all stars in a single M5 bin. Second, the IR data has been obtained with aperture sizes typically 4 - 5 times larger than the optical data on which most models have been based. Nevertheless, by analogy with early-type galaxies, it would seem that the spiral galaxy IR data can only support giant dominated models with small mass-to-light ratios. Dwarf enhanced models such as those calculated by Williams (1976) having $M/L \sim 50$ seem definitely ruled out.

Recently, Wynn-Williams et al. (1979) and Rieke et al. (1980) have considered models for the infrared emission of active spiral galaxy nuclei. The latter authors have argued that bursts of star formation having a low-mass cut-off in the IMF can account for most of the observed properties in M82 and NGC 253. A related result is that of Rieke and Lebofsky (1978), who find that significant 10 micron emission from the nuclei of spiral galaxies is quite common. Their measurements imply that such nuclei have a typical M/L_{bol} of about 0.2, a value that again suggests recent intense star formation. The cause behind such bursts and why they occur in some galaxies and not others is I believe a major unsolved mystery.

Infrared models for star formation on a more global scale have been constructed by Struck-Marcell and Tinsley (1978). These authors point out that UBV colors do not suitably distinguish age effects and cannot, for instance, discriminate between old galaxies with a recent star formation burst and truly young objects. They find that V-K colors provide about three-fold better age discrimination than U-V. With the hope of identifying possible young galaxies, Aaronson and Huchra (1980) have obtained IR data for a number of blue Markarians. The (reddish) V-K colors for these objects seem to favor the star-burst rather than young galaxy picture, assuming the Struck-Marcell and Tinsley models are even approximately correct. It is interesting, though, to consider the bluest object measured by Aaronson and Huchra - MK116, one of the so-called isolated extra-galactic H II regions of Sargent and Searle (1970).

This object has a V-K color of 0.5 $\pm$ 0.3, implying that some 50% of the stars formed in a burst about 3 x 10^7 years ago (see Struck-Marcel and Tinsley 1978). MK116 is probably the best case for a young galaxy, and a more accurate V-K color would be useful to pin down whether there are any old stars in it at all.

A minor controversy has arisen related to the stellar content in normal spiral galaxy nuclei. Using various optical line indices, McClure, Cowley and Crampton (1980) have argued that old horizontal branch stars rather than young main sequence stars are major contributors in the ultraviolet. However, the opposite conclusion is reached by Boroson (1980). The relevant IR observations suggest that in fact both mechanisms for producing UV light occur, but perhaps not in the same object. (Note that the overlap of galaxies in these two studies is rather small.) On the one hand, the late-type galaxies studied by McClure _et al_. show the strongest evidence for a decrease in [M/H], consistent with the downturn in CO index reported earlier. However, Rieke and Lebofsky's (1978) 10 micron measurements indicate considerable recent star formation in many spiral nuclei. Also, the two most extreme cases of young star contamination in Boroson (1980) - NGC 2681 and 5194 - do have strong CO indices, supporting the young star view. Nuclear (as opposed to large aperture) CO measurements for the objects in the Boroson and McClure _et al_. samples would be of interest in further pinning down the youth versus metallicity question.

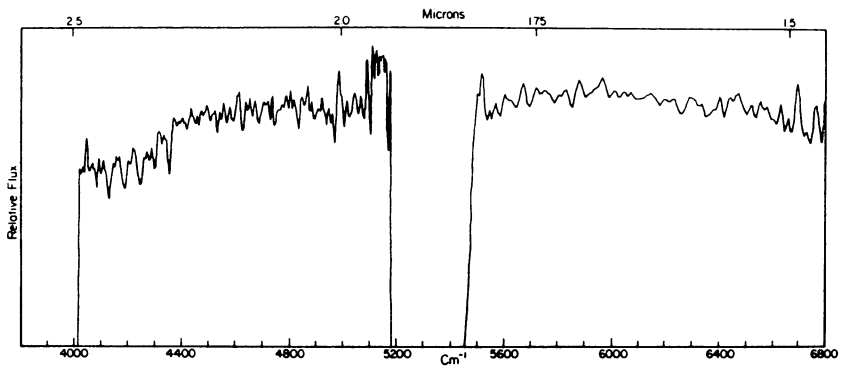

Figure 2. An infrared spectrum of the galaxy M81. The resolution is $\sim$ 8 cm^{-1} in the K-band region, and $\sim$ 16 cm^{-1} in the H-band region. Between 5000 and 5600 cm^{-1}, below 4100 cm^{-1}, and above 6600 cm^{-1} the spectrum is severely degraded by atmospheric extinction. The first five bands of first-overtone ^{12}CO are clearly visible. The broad continuum peak at 6000 cm^{-1} can be identified with the maximum in the continua of late K and M stars arising from the minimum in the H^- opacity.

Small aperture IR measurements of the semi-stellar nucleus in M31 have been obtained by Persson et al. (1980b) to test the proposal of Faber and French (1980) that the ratio of dwarf to giant light increases in going from the bulge to the nucleus of M31. The IR data does not support this contention. In particular, the CO index measured in a 2.5" aperture is 0.16 mag, identical to that found by Aaronson (1977) in a 107" aperture. Aaronson (unpublished data) has also measured the CO index of M31 in a 213" and 410" aperture, with the result being 0.16 mag in both cases. The CO index in this galaxy is thus constant over a factor of 164 in radius. Gradients in optical line indices attributed to [M/H] variations do occur in M31 (e.g. Cohen 1979), so it would seem that the CO index becomes saturated with [M/H] at the metal rich end.

In the next few years we can expect to see an increase in infrared spectroscopic studies of normal galaxies. The IR group at Arizona has been conducting such observations for the last few observing seasons. An example of an early effort is shown in Figure 2, which presents an FTS spectrum of M81 obtained by Aaronson and Boroson.

The first five first-overtone ^{12}CO bands are clearly visible in Figure 2, if little else, confirming that the index I have spoken of repeatedly is in fact really due to CO. The situation with regard to H_2O absorption is less clear. Although there is a hint of a downturn in the continuum above 4960 cm^{-1} and below 5700 cm^{-1}, the spectrum becomes so degraded by atmospheric extinction in the main region of interest that it cannot be regarded as either confirming or denying the presence of steam. As mentioned above, there is little hint of absorption due to the Ballick-Ramsay C_2 band at 1.8 micron, a strong signature of cool carbon stars. However, we can identify the broad continuum peak at about 6000 cm^{-1} as being due to the H^- opacity minimum which produces a maximum in the continua of cool K and M stars (cf. Catchpole and Glass 1974).

The spectrum in Figure 2 is too noisy to place a sound limit on the $^{12}C/^{13}C$ ratio, but this is a potentially very interesting number which spectra of only a little higher sensitivity can determine. In our own galaxy this ratio has been measured to vary from 90 in the sun to as low as 5 in some red giants (e.g. Dearborn, Eggleton and Schramm 1976). If mixing on the giant branch is responsible for the effect, we should expect to also find low values of the ratio in the giant-dominated light of other galaxies.

In closing, let me say that I have tried to demonstrate in this review how observations in the infrared have yielded important insight into many questions related to stellar populations that could not have been answered from optical data alone. With the development of large telescopes on Mauna Kea and Mt. Hopkins optimized for low background work, and continuing improvement in instrumental techniques (perhaps we will even see arrays someday), infrared studies in this fascinating area should continue to make a valuable contribution.

Preparation of this article was partially supported by the National Science Foundation.

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DISCUSSION FOLLOWING PAPER DELIVERED BY M. AARONSON

WYNN-WILLIAMS: What are the prospects of obtaining a good observational discriminant between populations of late-type giants and late-type supergiants in galaxies?

AARONSON: The prospects are good if you believe evolutionary models. Models predict that the later the galaxy type the stronger the CO index should be, because of the larger number of supergiants. Observationally the opposite is true, which indicates to me that supergiants do not dominate the populations except in very active regions of star formation. The decrease in CO index in late-type spirals is probably a metallicity effect.

TOVMASSIAN: You said that red supergiants are found in galaxies with signs of activity of their nuclei (M82, etc.). Does it mean that red supergiants are young stars?

AARONSON: I'm sure almost everyone would agree that supergiants are young stars.

PERSSON: With regard to the question of whether the U-V, V-K problem in elliptical galaxies is due to U-V or V-K, could you comment on the large CO band strengths measured for faint elliptical galaxies whose broad band colors are the same as those of globular clusters at the same blue broad band color, and second, on the recent IUE observations of elliptical galaxies which show that they have UV excesses.

AARONSON: The CO indices of even the very faint dwarf ellipticals are much stronger than those of globulars of similar U-V color, indicating that even in what are thought to be very metal-poor objects there is a very red, possibly metal-rich population. The IUE observations have in fact revealed the presence of a very hot component in elliptical and early-type spirals. The models that have been produced for this component predict significant contributions shortward of 2200 Å, but very little contribution at U.

THOMPSON: In NGC 2209 you commented that U-V was too blue but V-K was too red, and suggested that this effect could be due to a single carbon star in the beam. I would point out that carbon stars are much too deficient in the ultraviolet to produce this effect.

AARONSON: This object has a well-determined metallicity, [M/H] ~ -0.5, and age from the main sequence turn off (~0.8 billion years). The blue colors, as compared with galactic globulars of comparable [M/H], are from the young upper main sequence stars.

BECKLIN: Does the assumption, which everyone makes, that the IMF is a single power law have any validity and does this assumption make a big effect on the model results?

AARONSON: Although people usually use it, the assumption is certainly not a good one for our Galaxy, for example. Recent work by Scalo indicates an initial mass function broken into four parts, with the exponent generally ranging between 0 and 2. In terms of the models, the exponent is most critical near the turn-off point, but values in the range 0 to 2 do not greatly affect the colors that you see. You only get significant contributions from dwarf stars by having values of the exponent much greater than 2.

THOMPSON: It is important to look for carbon stars in galaxies, and it might be worthwhile to set up a photometric narrow band at 1.77 μm to detect the very strong Ballick-Ramsay band of C_2.

AARONSON: The absence of the 1.77 μm Ballick-Ramsay C_2 band in the FTS spectrum of M81 [Figure 2] provides, I believe, strong evidence against the presence of carbon stars.

ZUCKERMAN: Observations of carbon stars in intermediate age extra-galactic clusters may help to solve a venerable problem in stellar evolution—the lower limit to the main sequence mass of stars that eventually become carbon stars.

Another problem of more recent vintage concerns some of the extremely red AFGL objects. Many of these strong 10 and 20 μm sources are carbon stars. We don't really know if all of these extremely red stars are also very massive. (IRC +10216 probably contains a few solar masses in its expanding molecular envelope.) Observations of extra-galactic carbon stars (that are contained in clusters) at 10 and 20 μm may help to clarify this question.

AARONSON: That is an interesting point. I believe that the luminosities of objects such as IRC +10216 are much greater than the bolometric luminosities of the carbon stars in the Clouds, but it would be very interesting to observe some of these Cloud carbon stars at 10 μm to see if they do have any big excesses.

https://doi.org/10.1017/S0074180900075288 Published online by Cambridge University Press