INFRARED OBSERVATIONS OF GIANT ELLIPTICAL GALAXIES: (V-K) COLORS AND THE INFRARED HUBBLE DIAGRAM

Gary L. Grasdalen
Kitt Peak National Observatory and Department of Physics and Astronomy, University of Wyoming

ABSTRACT

The (V-K) colors of giant elliptical galaxies as a function of redshift are discussed. Present data are consistent with mild color evolution at $z \sim 0.45$. An infrared Hubble (redshift-magnitude) diagram is given. Cosmological models with $q_o = 0$ and no luminosity evolution are clearly excluded by the present data. A wide variety of models including those with $q_o = 0$ are permissible if luminosity evolution is included. Instrumental and programmatic implications of these results are summarized.

I. INTRODUCTION

In this contribution I will summarize the results of an infrared program aimed at directly observing the color and luminosity evolution predicted by big bang cosmological models for the stellar content of galaxies. In searches for cosmological tests an enormous amount of effort has already been expended in making optical observations of the first ranked elliptical galaxies in rich clusters of galaxies (e.g. Sandage 1975; Kristian, Sandage and Westphal 1978). This work has clearly demonstrated that these galaxies are highly uniform in their absolute visible luminosity as well as their energy distributions. Furthermore these early type galaxies contain little evidence for recent star formation, a fact which leads to the expectation that luminosity and color evolutionary effects will be both predictable and small for these systems. Since these galaxies are also the most luminous stellar systems in the universe they are logical candidates for use in delineating the relation between time and velocity that applies for the universe. The time scale of course is measured backwards from the present epoch by estimating the distance or light travel time to the galaxy from its apparent brightness. In applying this cosmological test it is crucial to accurately assess the past luminosity of the selected class of galaxies.

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II. (V-K) COLORS OF GALAXIES

The most direct test of the correctness of the predicted luminosity evolution due to stellar evolution is the expected change in the color of the galaxy. In Figure 1 we have plotted the energy distribution for a giant elliptical galaxy derived by Whitford (1971) for the optical spectrum and derived from the broadband infrared colors given by Frogel et al. (1978). Examination of this figure reveals that as a function of increasing redshift the observed V(0.55μ) or R(0.70μ) magnitudes refer to successively fainter portions of the energy distribution, while the K(2.2μ) magnitude will measure brighter portions of the energy distribution. Thus in attempting to observe color changes in elliptical galaxies it does not seem very profitable to use observed wavelengths shortward of the V magnitude band. The effect of the blanketing break near 0.4μ is catastrophic on the observed brightness, making observations shortward of the break exceedingly difficult. The (V-K) or (R-K) colors appear far more attractive choices. They also have a long baseline in wavelength which should enhance the evolutionary effects on the color.

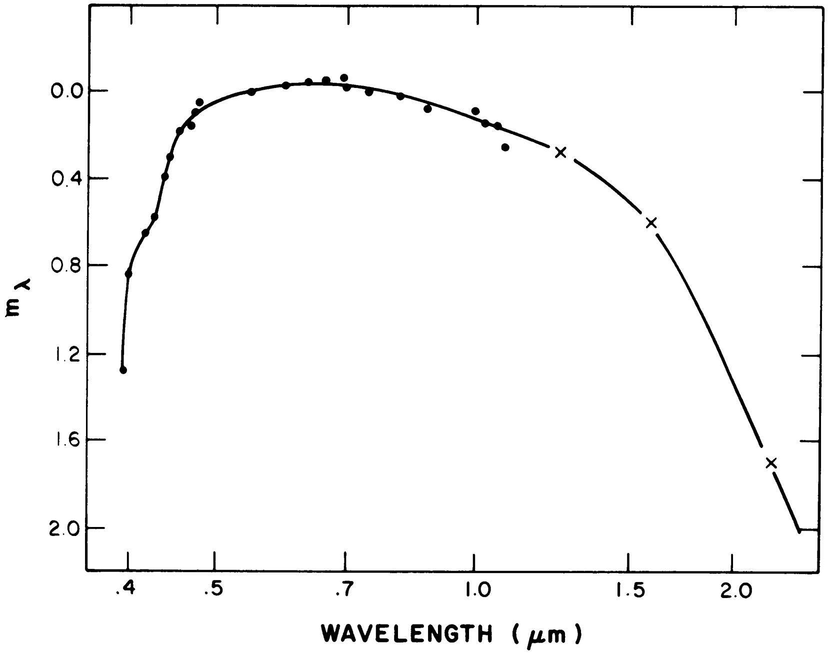

Figure 1. Energy distribution for a giant elliptical galaxy.

A program to measure the (V-K) colors of giant elliptical galaxies was undertaken at Kitt Peak National Observatory in 1974. Preliminary and erroneous results from that program have been previously reported

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(Grasdalen 1975, Frogel et al. 1975). The difficulty in those results arose from inadequate Fabry action in the implementation of the new InSb detectors and hence erroneous values for the beam size. (Rieke and Lebofsky 1979). The observations reported here were either made with more sophisticated systems or were rereduced with the corrected beam sizes. Except for a few nearby galaxies the V magnitudes were not remeasured but were taken from the photometry given by Sandage (1972b & c, 1973b). The V magnitudes were generally interpolated, occasionally extrapolated to the diaphragm size used to make the K observations using the growth curve given by Sandage (1972a). Galactic extinction was removed following the prescription given by Sandage (1973a) for A_V as a function of galactic latitude and then assuming that E(V-K) = 0.9 A_V (Sneden et al. 1978).

The results from this program are plotted in Figure 2. The solid curve in this figure is the expected (V-K) color as a function of redshift based on the energy distribution in Figure 1. For redshifts below 0.2 the data are in moderately good agreement with expectations. Unfortunately there are no galaxies in the redshift range 0.2 to 0.4. The two galaxies between z = 0.4 and 0.5, 3C 295 and 0024+16 have (V-K) colors slightly bluer than would be expected on the basis of the observed local energy distribution. The effect is not particularly large, only 0.25 and 0.5 mag. This is however the appropriate sign and approximate size for the expected color change (Tinsley and Gunn 1976).

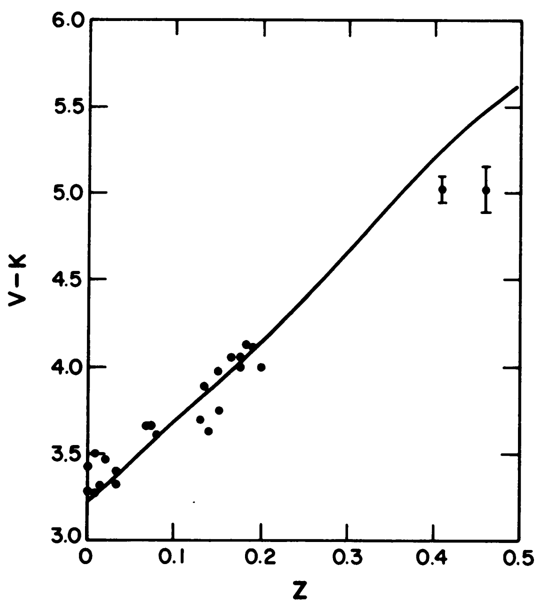

Figure 2. Observed and predicted (V-K) colors of elliptical galaxies.

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An obvious worry is that some spurious effect is mimicking the effect expected on evolutionary grounds. At redshifts beyond 0.4 the V magnitude refers to an emitted wavelength less than 0.4μ. This makes the observed V magnitude very sensitive to the metal content. The rather rare blue stars can also begin to influence this spectral region; especially worrisome in this regard is the possible influence of differences in horizontal branch morphology.

III. THE INFRARED HUBBLE DIAGRAM

The difficulties besetting the interpretation of the (V-K) colors illustrate why the optical portion of the spectrum as well as being observationally challenging is not a very attractive wavelength to observe early type galaxies at high redshift. The most directly interpretable data will be obtained at rest wavelengths beyond 0.4μ. Ground based observers are of course plagued by the very strong OH bands present in the night sky beyond 0.7μ. The severe effect of these bands can be seen by examining the spectrophotometric scans presented by Spinrad et al. (1976). Because of the enormous improvements in infrared detectors in recent years, the wide and dark atmospheric window at 2.2μ is the most attractive wavelength for ground based observations of distant galaxies.

To this end, as redshifts become available for more distant first ranked cluster galaxies (Spinrad 1975, Spinrad et al. 1976, Smith et al. 1979), infrared (2.2μ) observations were obtained. The relative ease with which photometric observations could be made prompted the thought that infrared photometry could be carried out on galaxies that are not visible at optical wavelengths at all. To test this idea I chose three 3CR radio sources which 1) had good radio interferometric observations that showed them to be classical double lobed radio sources (Pooley and Henbest 1974, Longair 1975), and 2) had been searched optically with deep photographs (Kristian, Sandage and Katem 1974, Longair and Gunn 1975). The 4-meter telescope was then used to make photometric observations at 2.2μ at a point midway between the two radio lobes. The beam size for these observations was 6.5". The linear intensity results and the final 2.2μ magnitudes for 3CR 427.1, 65 and 68.2 are given in Table 1. Clearly 2.2μ light was detected for 3CR 427.1 and 65. Simultaneously, H. Spinrad (this symposium) had succeeded in obtaining photographs of 3CR 427.1 and after many nights of spectroscopic integration has proposed a redshift of 1.11. Currently the galaxy associated with 3CR 65 has not been detected optically (Smith, Burbidge and Spinrad 1976).

In Figure 3 the available infrared data has been plotted as a Hubble diagram. The mode of plotting the data has been somewhat modified from past diagrams; only corrections for aperture size and galactic reddening have been applied to the data to produce K_{SM} the 2.2μ magnitude at a standard metric diameter. ($q_o = 0$ has been assumed in making that correction.) The position of 3CR 65 has been indicated

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as a vertical line and 3CR 68.2 as an upper limit. In comparing the data with the cosmological and evolutionary models, corrections for the variable rest wavelength of the observations have been incorporated into the predicted relations.

Table 1. 2.2μ Results for Double Lobed Sources

Source		Linear Reading σ	Integration Time 10^3 sec	2.2μ mag
3CR 427.1		11.6 ± 1.8	6.4	
		16.8 ± 2.6	3.2	
		10.7 ± 2.3	3.2	
	mean	12.7 ± 1.3	12.8	16.4 ± 0.1
3CR 65		6.5 ± 2.8	6.4	
		7.7 ± 1.9	6.4	
		8.0 ± 2.4	6.4	
	mean	7.4 ± 1.4	19.2	17.0 ± 0.2
3CR 68.2		-2.0 ± 4.2	3.2	
		2.2 ± 1.9	6.4	
		0.6 ± 2.0	6.4	
	mean	0.6 ± 1.4	16.0	>17.5 (3σ)

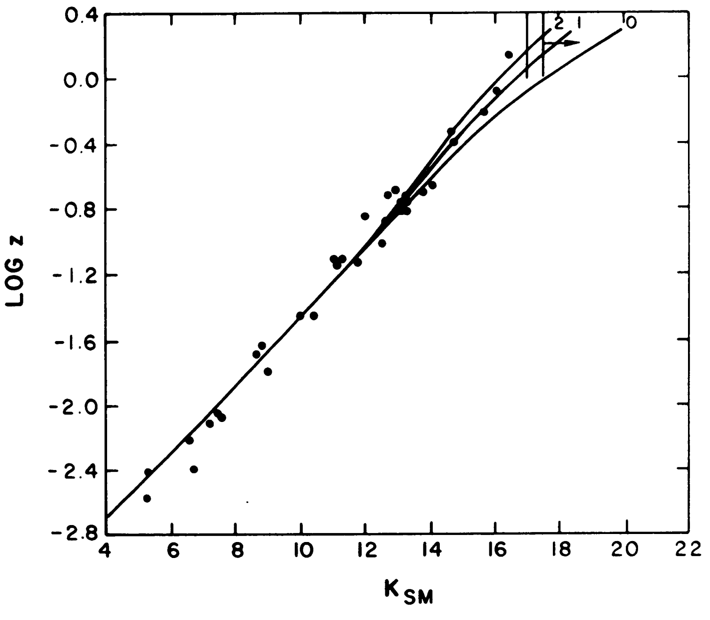

Figure 3. The observed infrared Hubble diagram. Cosmological models with q_o = 0,1,2 and no evolutionary corrections have been superposed.

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The predictions, also plotted in Figure 3, were made from cosmological models without any evolutionary corrections. The curves correspond to three values of the deceleration parameter $q_o = 0,1,2$. Examination of Figure 3 leaves no doubt that models with $q_o = 0$ and no evolution are ruled out by the present data. If evolutionary corrections are admitted the number of adjustable parameters becomes large enough to fit the data with any value of q_o larger than or equal to zero. The evolutionary luminosity calculations were taken from Tinsley and Gunn (1976). In Figure 4 we show the Hubble diagram with a particular set of $q_o = 0$, evolutionary predictions superposed. Here the parameter, X, used by Gunn and Tinsley to describe the main sequence mass function has been set equal to zero. This produces the fastest luminosity evolution, but is still consistent with the observed properties of nearby elliptical galaxies.

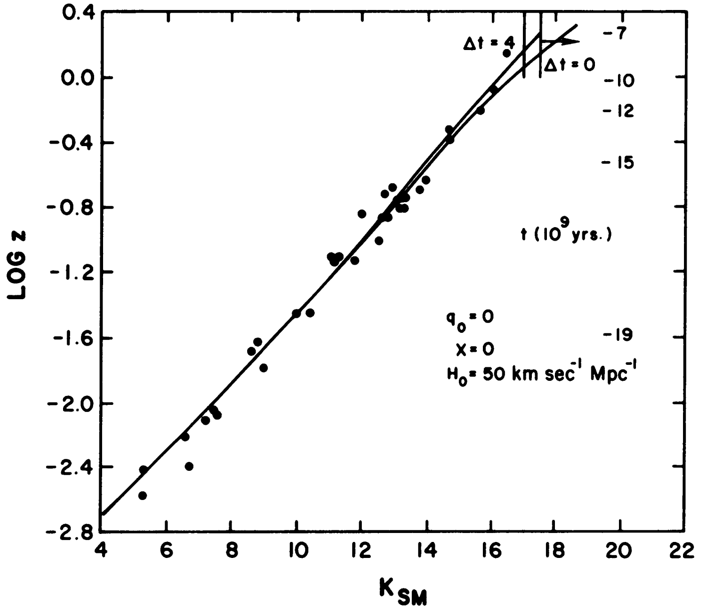

Figure 4. The observed infrared diagram: The parameter Δt is the time, in units of 10^9 years, between the big bang and the epoch of galaxy formation.

The curves have been drawn for two assumptions; Δt = 0, galaxies were formed immediately after the beginning of the expansion, and Δt = 4, galaxies were not formed until 4 x 10^9 years had elapsed since the beginning of the expansion. If we accept that quasars are at the nuclei of galaxies we cannot postpone the formation of galaxies beyond this epoch since quasars are already observed at that epoch. Clearly however, evolutionary models can be constructed that are compatible with the data.

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IV. CONCLUSIONS

For redshifts greater than ~0.7 it appears unlikely that ground based observations can succeed in making the sample adequately large. This fact arises from the faintness of galaxies in the ultra-violet portion of the spectrum. The distances involved are not especially large. If new redshifts are to be obtained they must come from space telescope observations of the blanketing break redshifted into the photoelectric infrared or from the rest frame ultra-violet features. Space telescope will be required to avoid the strong OH emission in the night sky in the first case and is required in the second case in order that very small angular apertures can be employed.

Our expectation that photoelectric and near infrared photometry give the most directly interpretable information on the luminosity evolution of elliptical galaxies is directly confirmed by the present data.

These considerations lead me to conclude that the development of high efficiency-low noise detectors in the wavelength range 0.7-2.4μ is a necessary requirement for the further progress of galaxian observational cosmology.

Our observations demonstrate that the remaining optically blank 3CR fields correspond to distant radio galaxies.

The presently available infrared redshift-magnitude diagram is consistent with cosmological models for which $q_0 = 0$ and only the effects of stellar evolution are included in the luminosity evolution of elliptical galaxies.

Finally we must caution that in order to accurately separate the effects of geometry and evolution it may be necessary to observe more rapidly evolving systems (i.e. late type galaxies), another task that will require the spatial resolution of Space Telescope.

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DISCUSSION

P. Veron: Why do you believe that the objects you have detected at the positions of 3CR radio sources are galaxies when Rieke calls objects with similar infrared properties found at the positions of flat spectrum radiosources QSOs?

Grasdalen: The radio sources are quite different. These are double-lobed sources without a central source. In the case of 427.1 the observed color from 1.25 μ to 2.2 μ is consistent with a red-shifted giant elliptical galaxy.

M. Burbidge: If one has to wait for the second generation of instruments on the Space Telescope to get deep red or near infrared response, perhaps one should pin hopes on forthcoming large ground-based telescopes (10-m class, or the Next Generation Telescope in the 25-m class).

Grasdalen: Yes, for the wavelengths around 2 microns where the air glow is rather small. However, for the photoelectric infrared (0.7 - 1.2 μ), the strong OH emission lines in the atmosphere make the Space Telescope much more attractive than the large ground-based telescopes of the future.

Peebles: Which are the stars that contribute most of the light at 1 to 2 μ? Are the evolution corrections as touchy in the infrared as the visible?

Grasdalen: The late giants dominate the infrared light. This has been demonstrated by Frogel and his collaborators, by showing that the CO band at 2.4 μ is quite strong in the spectra of giant ellipticals. Thus, the evolutionary corrections are as sensitive as the rest frame V-band corrections.

Scheuer: Could you and Dr. Rieke and Dr. Longair between you say how many of Longair's complete sample of 166 3CR sources still remain unidentified after the IR work you have just described?

Grasdalen: This question was answered by Longair.

Longair: Of the four 3CR radio sources which lie in empty fields in the statistical sample of 166 sources, two are 3C 65 and 68.1. 3C 65 has been studied with excellent plate material on at least three occasions and no identification has been found. If we accept Dr. Grasdalen's infrared object as an "optical" identification (and I see no reason not to), there are only three blank fields in the sample of 166.