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MAPPING THE STRUCTURE OF THE SOUTHERN MILKY WAY

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RESUMEN. Describimos un programa para hallar, clasificar y determinar las distancias de supergigantes débiles rojas en la parte sur de la Vía Láctea. El proyecto, el cual se encuentra en su quinto año, se está llevando a cabo completamente desde Chile y ha aumentado en más del doble el número de las supergigantes de tipo M conocidas en la Galaxia. Los principios de usar fotometría en banda angosta de supergigantes rojas para trazar la estructura del brazo espiral de la Galaxia, se describen y se comparan con los métodos usados en trabajos previos.

ABSTRACT. A program for finding, classifying, and determining the distances to faint red supergiants in the southern Milky Way is described. The project, which is now in its fifth year, is being carried out entirely from Chile and has more than doubled the number of known M-type supergiants in the Galaxy. The principles of using narrow-band photometry of red supergiants to map the spiral-arm structure of the Galaxy are described and compared to the methods used in previous work.

Key words: GALAXY-STRUCTURE

I. INTRODUCTION

The problem of determining the structure of our Galaxy has a long history, going back at least as far as William Herschel who in 1785 announced that the stars we see in the sky form an immense system, finite in extent and considerably flattened. Since then we have gradually come to realize that our Galaxy is comparable in size and shape to innumerable other galaxies that we routinely photograph with our telescopes — namely the ones we call the giant spirals. However, it was not until the 1950s that we had the techniques needed to start the difficult process of mapping out the spiral arms of our own Galaxy.

As part of this continuing process, I have been collaborating with Edgardo Costa of the Universidad de Chile and Jack MacConnell of the Space Telescope Science Institute in an attempt to locate the spiral arms through observations of red supergiant stars. These stars are quite numerous and belong predominantly to the spiral-arm population; furthermore, their distances can be determined by a type of narrow-band photometry that we have developed for this purpose. Our project, now in its fifth year, is not of a kind that can be completed in one or a few observing runs since we must start by finding our program stars by sifting through thousands of candidate stars to identify the ones that are true supergiants, far enough away to be useful as galactic-structure indicators. We have been concentrating on the southernmost third of the galactic plane — the part inaccessible from northern observatories — and all of our observations have been made from Chile.

The methods used in our project are discussed in Section IV, and a brief report on the current status of the project is given in Section V. First, however, I would like to outline the historical background of galactic-structure studies and to explain, in general terms, the special problems that are faced in work of this type.

II. HISTORICAL BACKGROUND

Progress in understanding the structure of the Galaxy has come about primarily through a small number of large steps, rather than as a continuous development. The six steps that now seem the most important are listed in Table 1. From a modern point of view, little happened in this field between Herschel's (1785) first estimate of the Galaxy's size and shape and Shapley's (1918) realization, more than a century later, that our Sun occupies a position far removed from the center of the system. Herschel's conclusions were based on star counts, while Shapley's were derived from the highly asymmetrical distribution of globular clusters in the sky. In the meantime, the spiral shapes of the spiral nebulae were noted visually with large telescopes and, around the beginning of the 20th century, were recorded photographically, but it was not at all clear that these shapes had anything to do with the structure of our Galaxy. Shapley, at the time of the work cited, considered our Galaxy to be a unique object and the spiral nebulae to be relatively small, diffuse objects located outside it. Shapley's work caused a sensation, as it made the Galaxy enormously larger than previously believed and placed the solar system far from its center. In fact, Shapley overestimated the size of the Galaxy, and it is easy to understand why he found it hard to believe that the spiral nebulae could be systems of comparable scale.

TABLE 1. Milestones in Understanding the Structure of the Galaxy

Investigator(s)	Date	Principal Results
W. Herschel	1785	Elongated shape and finite size of Galaxy
H. Shapley	1918	Off-center position of Sun in Galaxy
R. Trumpler	1930	Pervasiveness of interstellar absorption
W. Baade	1944	Populations I and II
W. Morgan and colleagues	1952-55	Spiral structure from distribution of O and B stars
J. Oort and others	1950s	Distribution of neutral hydrogen from 21-cm observations

The extragalactic nature of the spiral nebulae became clear in the following decade, primarily as a result of Hubble's (1925) identification of Cepheid variable stars in the Andromeda Nebula, M31. Although Hubble's result is universally considered a milestone in elucidating the nature of galaxies, I have not included it in Table 1 because it had no direct bearing upon the structure of our own Galaxy. Nevertheless, it is fair to say that ever since 1925 our Galaxy has generally been regarded as a spiral, one that would look much like M31 if viewed from a similar distance and angle. Yet three decades were to elapse before the spiral arms of our Galaxy were shown to exist by direct observation.

The open star clusters, which lie in the plane of the Galaxy, have played an important role in determining the structure of the disk because their distances can be found more securely than those of individual stars. Yet the distances obtained from the apparent brightnesses of cluster stars can be greatly in error if no allowance is made for absorption by interstellar dust. It was Trumpler (1930) who realized that interstellar absorption is not limited to the dark clouds that are seen in photographs of the Milky Way but pervades the entire galactic plane, so that clusters appear fainter than would be expected from their angular diameters. Later, photometric methods were developed to correct for interstellar absorption, taking advantage of the fact that the absorption is wavelength-dependent, making stars appear redder; thus one can measure the reddening and apply the corresponding correction for the effect of absorption on the apparent magnitude.

The idea of two stellar populations came from Baade's (1944) photographic study of the Andromeda Galaxy and its companions carried out with the 100-inch telescope at Mount Wilson. On deep plates taken in red light he was able to resolve the nucleus of M31 into individual stars, while on blue plates the only stars seen individually were the blue supergiants of the spiral arms. This indicated that the brightest stars of the nucleus are red giants, as in the globular clusters of our Galaxy. In this way, both M31 and the Galaxy came to be understood as consisting of two major components, which Baade termed 'populations': an old, spherically-distributed component, whose brightest stars are red, found in the nucleus and halo (Pop. II), and a younger component, whose brightest stars are blue, found in the flat, rotating disk (Pop. I). The spiral arms seen in many galaxies were then recognized to be sites of recent star formation, where short-lived O and B-type supergiants are found near their places of origin, illuminating the gas clouds in their vicinity.

Thus by 1950 astronomers had arrived at essentially the modern concept of the nature of our Galaxy, yet there was still no direct evidence that the luminous material of the disk is organized into spiral arms. The problem, of course, is that our solar system lies in the same flat plane as the spiral arms; a spiral viewed edge-on reduces to a line, and no kind of imaging of the Galaxy from the Earth will ever show a structure that can be described as "spiral". There is no hope of seeing our Galaxy from the outside, as we do the other galaxies, and the scale of the system is so great that even with Space Age technology we cannot expect to move appreciably above or below the plane in order to gain some perspective on the distances to different stars, star clusters, or gas clouds. All we can do is scan the "horizon" — the Milky Way — recognizing whatever objects we can, and using any method we can devise to judge their distances. Once the distances to individual objects have been determined, we can plot them on a map of the galactic plane to see if any patterns emerge.

In the decade of the 1950s, two new lines of investigation were developed by optical and radio astronomers, leading at last to concrete evidence that the Galaxy can properly be called a "spiral". Morgan and his colleagues combined spectral classification with photoelectric photometry to determine the distances to groupings of O and B-type supergiants; these were found to be strung out along short arcs which could reasonably be identified with segments of the elusive spiral arms. Their method of distance determination, with modifications, has been applied subsequently to several other types of stars and may be considered the forerunner of the technique that my colleagues and I are now applying to the problem; we will, therefore, consider the principles of this method more fully in the next section. At about the same time as optical astronomers were first succeeding in finding the arms, radio astronomers in the Netherlands and Australia stole the thunder with their highly successful application of a very new technique: the mapping of neutral hydrogen gas in the Galaxy through observations of its spin-flip transition at a wavelength of 21 cm (see the summary of this work by Oort, Kerr, and Westerhout 1958). In this case, the observer sweeps in frequency over the spectral line at each pointing of the telescope, obtaining (through the Doppler effect) the distribution of the velocities of hydrogen atoms along the line of sight. The velocity distributions proved to be clumpy, suggesting that the gas was organized into clouds, arcs, or, on a larger scale, arms. Distances are obtained only indirectly by this method, by comparing the observed velocity distributions to those calculated from a mathematical model of the rotating Galaxy. Since the optical and radio methods of locating the spiral arms are fundamentally different and deal with different components of the system, it is hardly surprising that they produced rather different pictures of the spiral-arm structure. There is, however, enough correlation between the results of the two methods that there is general agreement as to the reality (and names) of the major arms, at least in the vicinity of the Sun.

III. OPTICAL METHODS OF DETERMINING SPIRAL STRUCTURE

To investigate the distribution of visible matter in the plane of the Galaxy, we must identify objects whose precise nature can be specified observationally so that absolute magnitudes can be assigned and distances calculated. It is clear that not all kinds of objects are equally useful for this purpose. If we use stars, they must be of a type that is found preferentially in the arms; since the arms are understood as regions of recent star formation, this is best accomplished by using types of stars that are necessarily very young, so that they haven't had time to move far from their places of origin. Stars that are certain to be young include the hot upper-main-sequence stars of types O and B, supergiants of all types, and Cepheid variables, all of which are high-luminosity stars that are producing energy at such a prodigious rate that they can't do it for very long. High-luminosity stars have the additional important advantage that they can be detected at large distances; young stars of lower luminosity, such as T Tauri stars or chromospherically-active M dwarfs, are of much less utility in galactic-structure studies. The most essential requirement is that we must be able to determine the distance, using observational material that can reasonably be obtained for stars of rather faint apparent magnitude; this means there must be a way of judging, on the basis of the star's spectrum, its absolute magnitude. Ultimately the quality of galactic-structure maps obtained from stellar observations will depend upon the accuracy with which absolute magnitudes can be assigned on the basis of simple observations. And if the star's apparent magnitude is to be used as the indicator of its distance, we must know how to correct it for the effects of interstellar absorption. [The latter requirement can be avoided if we use extended objects, such as clusters or H II regions, since then the angular diameter can be used as the distance indicator. Space does not permit consideration of this interesting approach, which in any case is limited by the accuracy to which intrinsic diameters can be assigned]. Finally, the type of object used must be reasonably common; in general it is the common, "normal" stellar types whose absolute magnitudes are known most precisely, and in any case a rare type of object, no matter how accurately its distance can be determined, will never provide much information about the structure of the Galaxy.

Morgan and his colleagues chose to observe the hot, luminous supergiants of types O and B because they are necessarily young and their distances can be determined by a combination of photometry and spectroscopy. Furthermore, these stars are the source of ultraviolet radiation that causes the gas clouds in their vicinity to glow brightly, and it is these bright gas clouds, in other galaxies, that produce the structures we call spiral arms. Thus there is no question that these stars are excellent spiral-arm indicators. The observations obtained by Morgan et al. were very simple, consisting of classification-dispersion spectroscopy and broad-band two-color photometry. Let us consider how these observations lead to a determination of the distance.

Distances are obtained from a comparison of observed and intrinsic properties. Photometry gives us, very accurately, the apparent quantities: apparent magnitudes, which depend upon the distance and interstellar absorption, and color indices, which are affected by interstellar reddening. Spectroscopy, on the other hand, reveals the intrinsic nature of the star — that is, its temperature and luminosity class — on the basis of its spectral lines, the strengths of which are independent of distance or the effects of interstellar dust. Mathematically, the difference $V - M_V$ between the apparent and absolute visual magnitudes is related to the distance d (in parsecs) as follows:

$$V - M_V = 5 \log d - 5 + A_V \quad (1)$$

where A_V is the interstellar absorption in the visual region (in magnitudes). The apparent magnitude is given directly by the photometry, the absolute magnitude comes from the spectroscopy (i.e. from a calibration of the absolute magnitudes corresponding to the various two-dimensional spectral types on the MK system), and the interstellar absorption draws from both types of observation: A_V is considered to bear a fixed relation to the color excess, which is the difference between the photometrically observed color index and the value expected for the spectral type. Thus in the early work of Morgan and his colleagues, the two-dimensional spectral classifications and the two-color photometry played equal roles.

At about the same time, H. L. Johnson established the three-color UBV photometric system (Johnson and Morgan 1953) and showed that the inclusion of an ultraviolet filter makes it possible to separate the effects of reddening and temperature, at least for stars of types O and B. This is because the ultraviolet spectral region of hot stars is strongly depressed by absorption by neutral hydrogen atoms in the $n = 2$ level, and this depression is so sensitive to temperature through this range of spectral type that, in the two-color diagram of U-B vs. B-V, the relation for normal unreddened stars is steeply inclined to the reddening line. Thus, if the star observed can be assumed to be a normal star of type O or B, it is possible to deduce its intrinsic temperature and its color excess (and hence the visual absorption) from the UBV data alone, either algebraically by the so-called "Q-method" of Johnson and Morgan or graphically, using the two-color diagram, as illustrated by Morgan and Harris (1956).

Note that the UBV photometry measures a spectroscopic (intrinsic) quantity — the strength of absorption by neutral hydrogen in the ultraviolet — as well as the usual photometric quantities. In this way the photometry can take over one of the functions of spectroscopy, i.e. the determination of intrinsic temperature, so that the absorptions A_V can be obtained by photometry alone. But UBV photometry is unable to assign luminosity classes or absolute magnitudes to O and B stars, since the intrinsic relations for dwarfs, giants, and supergiants in the two-color diagram are nearly the same. Hence for the problem of finding distances to individual stars, MK classifications are still needed for the essential role of assigning absolute magnitudes, as well as for checking that the star is of a type for which the methods of UBV photometry are applicable.

An additional step can be taken if the stars in question tend to belong to clusters or associations. One can then attempt to identify the main sequence in a color-magnitude diagram and determine the distance of the group by main-sequence fitting. When this is done, the distance is obtained from the photometry alone, and the spectroscopy, if available, is used only for confirmation. Stars that are good spiral-arm tracers do, indeed, tend to be found in clusters and associations, although the latter are loose configurations which merge smoothly into the surrounding arms. A special problem arises when the line of sight runs approximately tangent to an arm, for then one sees spiral-arm material over a large range of distance and it may not be at all obvious how to assign stars to groupings at specific distances.

The distances derived for groups of stars, and hence the spiral-arm patterns defined by them, can be influenced by the way individual stars have been assigned to the groups, much as the outcome of an election can be affected by the way the population is divided into voting districts. On the other hand, distances obtained for individual stars, which necessarily are based upon spectroscopic luminosity classifications of some sort, will inevitably have rather large uncertainties due both to errors in classification and to the dispersion in absolute magnitude within any luminosity class. It is therefore debatable whether it is better to plot all the individual stars in galactic-structure diagrams or to assign the stars first to groups and to plot a smaller number of better-determined points.

When Morgan, Code, and Whitford (1955) published their individual luminosity classifications for 1270 OB stars, they declined to tabulate their individual distances. Rather, the individual distances were used as a guide to the assignment of stars to physical groupings or associations (Morgan called them "aggregates"), and the galactic-structure diagram derived from this material (and published earlier by Morgan, Whitford, and Code 1953) contains only 35 points. These points were sufficient, however, to define three spiral arms that are still recognized today: the Local Arm containing the solar system, the outer Perseus Arm containing the Double Cluster, and an inner arm which has come to be known as the Sagittarius Arm.

Figure 1 is a schematic galactic-structure diagram, similar to the one plotted by Morgan et al. (1953) but based on more modern material. Stars and other objects can be placed in such diagrams by plotting their distances and galactic longitudes in circular coordinates centered on the Sun. The position of the Galactic Center (G.C.), at longitude 0° and an assumed distance of 8 kiloparsecs, is shown for reference. The main features of the diagram — the Perseus, Local, and Sagittarius Arms — are the ones identified by Morgan et al. (1953). The main difference with respect to the early work is that the Sagittarius Arm is shown extending far to the left, toward longitudes 280 - 290° which occur in the Carina region of the southern Milky Way; accordingly this arm is now sometimes called the Sagittarius-Carina Arm. The Carina region is particularly rich in supergiants, clusters, and nebulae and has lured many investigators of galactic structure to southern observatories, since it is totally inaccessible from the north. The interpretation of the Carina region is difficult, as we are looking along a spiral arm and see Population I material at a wide range of distances, and it is not even obvious that this material is connected to the Sagittarius Arm: an alternative arrangement which treated the Carina Arm as an extension of the Local Arm was considered by Bok (1959).

The features of Figure 1 are discussed more fully by Humphreys (1976). These include the "Centaurus Spur" jutting inward from the Sagittarius-Carina Arm, and the Norma-Scutum Arm closer to the Galactic Center. The reality of the Norma-Scutum Arm is still considered doubtful, as it is based on only a few stars and is heavily obscured by the dust of the Sagittarius-Carina Arm.

Most of our knowledge of spiral-arm structure is based on observations made in the blue part of the spectrum. This spectral region is a logical choice for studies of OB stars which are bright in the blue and are best classified in that region. Also, two of the main tools of the trade — MK classification and UBV photometry — specifically employ the blue spectral region. But absorption by interstellar dust is very strong in the blue and will always present a problem for studies of distant stars in the galactic plane. Radio (21-cm)

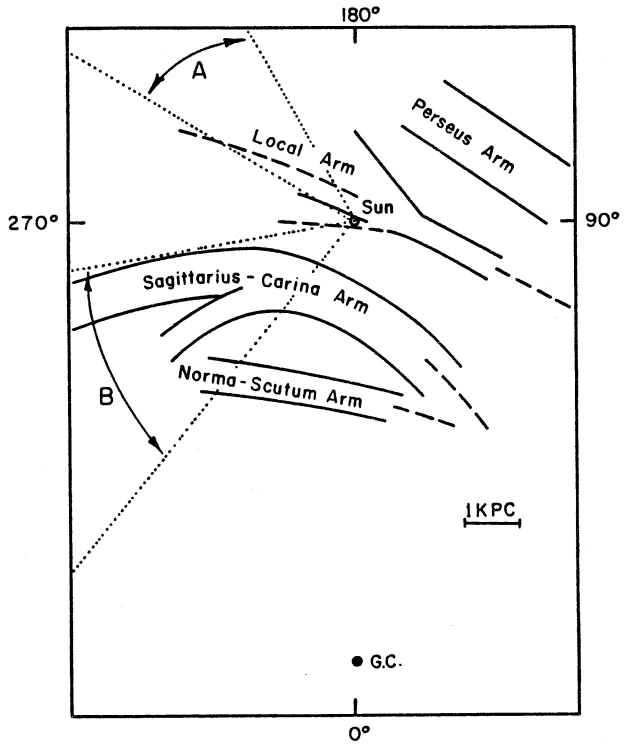


Fig. 1. Schematic galactic-structure diagram, showing the spiral arms revealed by optical observations. Positions of the Sun and Galactic Center (G.C.), at an assumed distance of 8 kpc, are indicated. Sectors labeled A and B refer to the project described in Section V. Adapted from a drawing by Humphreys (1976).

observations penetrate the dust, but they do not detect stars or other optically-observable features.

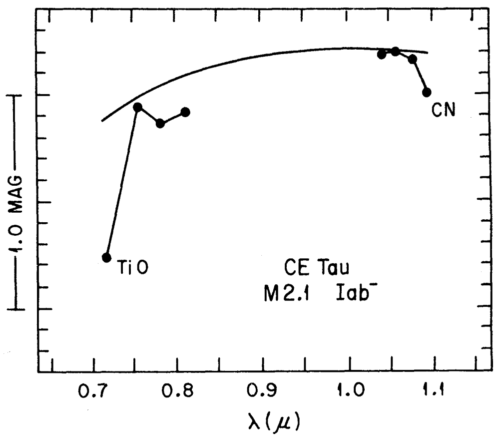
Our project makes use of the near-infrared spectral region where absorption by interstellar dust, while not negligible, is about four times less than in the blue. We are hopeful that this reduced absorption will result in a better view of obscured regions such as the Norma-Scutum Arm, so that we will see their structure more clearly through better distance determinations for larger samples of stars. The stars we are observing, the red supergiants, are intrinsically the most luminous stars in the near infrared and can be seen at great distances. Finally, the near-infrared spectra of these stars contain strong, broad absorption features — bands of the TiO and CN molecules — that are ideal for two-dimensional classification at low spectral resolution. In the next section we describe our narrow-band photometric system which provides both the spectroscopic data and the photometry needed to determine the distances of red supergiants.

IV. EIGHT-COLOR PHOTOMETRY AND ITS APPLICATION TO RED SUPERGIANTS

The eight-color system of narrow-band, near-infrared photometry was established to provide a convenient way to obtain basic photometric and spectroscopic information on late-type stars (Wing 1971). The near-infrared region was chosen because it contains both strong molecular bands and clear continuum points in most cool stars, in a region where they are bright. The eight filters include the best available continuum points and both carbon stars and stars of type M, and the strongest bands of TiO, VO, and CN are measured when present.

In designing the system, special attention was given to the M supergiants because they show bands of both TiO and CN in appreciable strength. Since both of these molecules have extensive, overlapping band systems, it is difficult to measure them separately when both are present or to find continuum points that are not contaminated. In fact we use an iterative procedure to obtain separate indices of TiO, CN, and color temperature in M stars (White and Wing 1978).

The magnitudes of standard stars on the eight-color system (Wing 1979, and unpublished) are expressed on an absolute flux system so that the data for program stars reduced relative to them can be directly compared to blackbody curves or energy distributions from models. The data for a typical M supergiant, 119 CE Tau, are shown in Figure 2 to illustrate the procedure used. Filters 1 and 3 (in order of wavelength) are depressed principally by TiO, and filters 4 and 8 by CN. To obtain indices of the strengths of these bands, we fit a blackbody curve to the spectrum (by finding the curve that passes through one point in each of the two sets of filters and above the other points) and measure the depression at each filter with respect to this blackbody continuum. These depressions, expressed in magnitudes, are the spectroscopic quantities provided by this photometry, and like spectroscopic equivalent widths, they are independent of reddening.



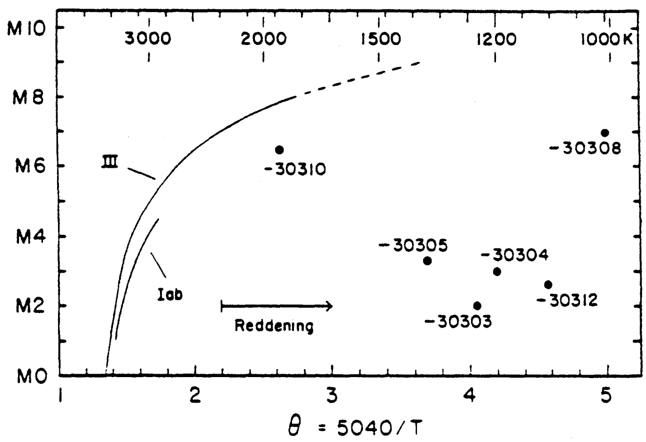


Fig. 2 (left). Eight-color photometry of the M supergiant 119 CE Tau. Absolute flux per unit wavelength interval, on a magnitude scale, is plotted against wavelength in microns. A blackbody curve for 2905 K has been fitted to the spectrum, with allowance for CN absorption at filter 2. Filters 1 and 8 are depressed by TiO and CN, respectively, leading to the classification M2.1 Iab$^-$.

Fig. 3 (right). Color-spectral type relation for the eight-color system. The spectral type, based on TiO strength, is plotted against the reciprocal color temperature, obtained by fitting blackbody curves to the data. Relations for unreddened class III giants and class Iab supergiants are shown. Reddening moves stars to the right; the length of the arrow corresponds to a color excess of E(B-V) = 1.0 mag. Several heavily reddened M supergiants, identified by IRC number, are plotted. From Warner and Wing (1977).

After small corrections have been applied for the contamination of filters 1 and 2 by CN, the depression at filter 1 is used as our TiO index. This filter, centered at 7120 Å and 60 Å wide, measures the strongest of the TiO bands, and the index defined in this way has been found to correlate very well with spectral types on the MK system (Wing and Yorka 1979). The CN index, defined as the average of the depressions at filters 4 and 8, is quite insensitive to temperature but correlates well with MK luminosity class (White and Wing 1978). Thus we obtain two-dimensional (temperature/luminosity) spectral classifications from the indices of TiO and CN (see also the discussion by Wing and White 1978).

The photometric quantities given by the eight-color photometrv are the apparent infrared magnitude I(104) measured at 10400 Å (filter 5) and the color temperature, obtained from the blackbody fit. For the latter, it is convenient to use the reciprocal color temperature $\theta = 5040/T_c$, since this quantity is proportional to a conventional color index (magnitude difference) yet avoids the problem that different continuum points are used for different types of stars. The blackbody continuum found for CE Tau in Fig. 1 has the values $\theta = 1.735$ and $T_c = 2905$ K, indicating a moderate degree of reddening.

The reddening $\Delta\theta$ is obtained by comparing the observed reciprocal color temperature to the value expected for the star's spectral type. In Figure 3, the smooth curves are the intrinsic relations for stars of luminosity classes III and Iab, and the dots are the observed values for a set of heavily-reddened IRC stars in the direction of the Galactic Center (Warner and Wing 1977). The horizontal displacement in this diagram gives $\Delta\theta$, and the absorption at 10400 Å, for a normal reddening law, is $A(104) = 1.25\,\Delta\theta$.

Distances are obtained from the eight-color photometry by a procedure that is fully equivalent to the one described in Section III, except that here all the information comes from the narrow-band photometry and equation (1) is rewritten as

$$I(104) - M(104) \;=\; 5\log d - 5 + A(104) \;, \qquad (2)$$

where the apparent magnitude I(104), absolute magnitude M(104), and interstellar absorption A(104) are all evaluated at 10400 Å. The main source of uncertainty in the distances obtained by this technique is likely to be in the calibration of the CN index in terms of absolute magnitude. We have values of M(104) for a number of M supergiants that belong to clusters of known distance, but further work is needed to learn the width of the CN - M(104) relation. Our current observing program includes additional cluster members to help clarify this point.

V. THE SURVEY FOR M SUPERGIANTS

Red supergiants have not previously been used as spiral-arm tracers for several reasons. The methods that have worked so well for OB stars are not appropriate for red stars, whose spectra in the blue region are faint and extremely complex. Luminosity classes are difficult to assign, at least in the blue. Even survey work has been conducted primarily in the blue region, thereby discriminating against the discovery of red supergiants.

A decade ago, White and Wing (1978) published eight-color photometry for nearly all M-type supergiants then known in the Galaxy — a mere 128 stars, an order of magnitude less than the number of OB stars available to Morgan and his colleagues. Although it was shown that M supergiants can be classified accurately and efficiently by the narrow-band technique, there were simply not enough of them to provide much information about galactic structure, especially in the southern hemisphere.

However, an infrared spectral survey carried out by MacConnell with the Curtis Schmidt telescope on Cerro Tololo indicated that red supergiants might be much more common than previously believed and should be reconsidered as possible spiral-arm tracers. Using an objective prism and I-N plates, he surveyed the entire southern Milky Way in a band approximately 13° wide (MacConnell, Wing, and Costa 1986). By employing extremely low dispersion (3400 Å/mm at the A band), long exposures, and unwidened spectra, he was able to reach infrared magnitudes around I = 13. On such plates, faint red stars have a characteristic wedge-shaped appearance. They cannot be classified, since at this dispersion not even the TiO bands can be seen unless the type is very late. However, from the early survey work of Nassau, Blanco, and Morgan (1954) and Blanco and Münch (1955) it was known that stars with tapered spectra on near-infrared plates often turn out to be late-type supergiants, their redness accentuated by interstellar reddening. MacConnell was finding literally thousands of these stars on his plates; the problem was to distinguish the true supergiants from the ordinary M giants.

We have, in fact, been employing two independent methods to determine the luminosities of the supergiant candidates. In 1984 we started collecting eight-color photometry for as many of these stars as possible, and a year later, with the participation of Costa, we started a parallel program of CCD spectroscopy, also in the near-infrared region (MacConnell, Wing, and Costa 1987). The spectra, mostly taken at the CTIO 1.0-m and 1.5-m telescopes and the 2.5-m telescope at Las Campanas, have sufficient resolution to show the luminosity-sensitive Ca II triplet clearly. Although we are able to determine distances for these stars from the eight-color data alone, the CCD spectra provide important supplementary information of three kinds: (1) they allow the recognition of unusual types of stars such as S stars which might otherwise be misinterpreted as M supergiants; (2) they give classifications for reddened early-type stars; and (3) they provide luminosity classes from the Ca II triplet that are independent of CN. An important by-product of this study will be the comparison of luminosities from CN and from Ca II for a large set of stars.

The eight-color photometry has been carried out primarily with the CTIO 1.0-m telescope, which proves to be the ideal size for this work. Two years ago, we were able to report that 117 M-type supergiants, mostly new, had been confirmed by eight-color photometry, out of 385 candidates tested (Wing, MacConnell, and Costa 1987). I no longer know the count of M supergiants found, but the success rate of ~30% has been roughly maintained and the number of candidates tested is now more than 750. Certainly the number of new M supergiants found by our project exceeds the number previously known in the entire Galaxy. And as our knowledge of galactic M supergiants increases, so does their usefulness is delineating the spiral arms of the Galaxy.

How many more red supergiants can be found in this way? Don't we have enough already? When should the search stop? Is it worth the telescope time to continue? These are questions that are bound to be asked — and that we periodically ask ourselves. The project has used a substantial amount of telescope time, but mostly bright time on small telescopes which is of limited use for other programs. We do intend to continue the follow-up observations, for a reason we consider very important: if we were to stop now, our data would present a very distorted picture of the Galaxy! MacConnell's objective-prism survey covers the southern galactic plane uniformly, but the follow-up observations have been decidedly non-uniform, being dictated both by telescope scheduling and by the availability of coordinates and finding charts for the candidate stars. Our work to date has been concentrated in two sectors, labeled A and B in Figure 1. In sector A (longitudes 210 - 240°, including constellations Monoceros through Puppis) the observations are now complete and are being prepared for publication. In the interesting sector B (280 - 320°, Carina - Norma) the number of candidate stars is larger, and the work is progressing well. On the other hand, work has barely begun in the direction of the Galactic Center, although Warner and Wing (1977) have shown that the dust of the Sagittarius Arm can be penetrated in the near infrared to reveal supergiants behind it. Finally, it would be a mistake not to cover the region between sectors A and B, dull as it may seem on the basis of existing data; we won't know what's not there until we look!

The survey for M supergiants described here has been made possible by the clear skies and excellent facilities at Cerro Tololo Inter-American Observatory. My colleagues and I would like to thank the CTIO Directors, staff, and telescope allocation committees — past, present, and future — for their support and encouragement.

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