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Dark Matter and the Missing Mass in the Milky Way Galaxy

Phillip K. Lu [1,2,3]

(Center for Galactic Astronomy Western Connecticut State University)

and

(Van Vleck Observatory, Wesleyan University)

Abstract

A study to determine the galactic gravitational force law $K(z)$, and local mass density using faint dwarf F–stars as tracer objects is in progress. The primary objective of this investigation is to search for evidence of thick disk and dynamic study of the missing mass and dark matter in the disk of the Milky Way Galaxy.

Objective–prism plates covering approximately 100 square–degrees centered at the South Galactic Pole using UK Schmidt films and Michigan Curtis Schmidt plates are now completed. Using a 1.5 degree prism with a dispersion of 1360Å/mm, baked IIIa–J emulsion and exposure time of 90 minutes, the new thin–prism spectra yield a set of uniformly selected F–stars to a limiting magnitude of 16.5. Observations using direct CCD photometry with *uvby* colors and spectroscopy using a 2D–Frutti system at a dispersion of 43Å/mm will provide the necessary halo F–stars for the investigation of the velocity distribution, the dynamic determination of the missing mass.

1. INTRODUCTION

A project to determine the galactic gravitational force law, $K(z)$, the local mass density and dark matter in the Milky Way Galaxy using faint main–sequence F–stars as tracer objects to one kpc is now in progress. The primary objectives are to investigate the velocity distribution, the search for evidence of a thick disk, dynamical study of the missing mass and dark matter in the galactic disk.

The dynamic determination of the total mass density in the solar neighborhood by

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[1]Visiting Astronomer, Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

[2] Sabbatical Leave at the Cerro Tololo Inter-American Observatory, La Serena, Chile.

[3] Visiting Professor, Chinese National Academy of Sciences, and Center for Astrophysics, the University of Science and Technology of China, Hefei, Anhui, the People's Republic of China.

means of the stellar velocity distribution has been recognized as a very difficult task. Some of the early investigations of this problem were made by Oort (1932) and led to the first suggestion of missing mass in the Galaxy. The nature of the missing mass has been attributed to the dark matter. In the 1930's, these dark and invisible objects included low luminosity and low mass stars, brown and white dwarfs, neutral hydrogen content in the Galaxy and black holes. The discovery of the neutral hydrogen line 21cm wavelength and at 1421MHz has setoff an intensive activity within radio astronomy to detect the extent of this cold and none optically luminous neutral hydrogen matter.

Recent dynamic studies using giants and nearby A and F–stars have suggested that about half the total matter density near the Sun is unaccounted for (Bahcall 1984a, b, c; Bahcall and Casertano 1985; Bahcall, Hut and Tremaine, 1985). It is not clear, however, whether this discrepancy is a localized phenomenon confined to the solar neighborhood or is a general property of the Milky Way Galaxy, although this invisible mass must be in a disk with a scale height not exceeding 700pc (Bahcall, 1984b).

The distribution of mass density and stars perpendicular to the galactic disk is generally determined by comparing the observational data with the results from a theoretical model assuming an ellipsoidal mass distribution. The component of the gravitational force perpendicular to the plane of the disk is denoted as:

$$D(z)=D(o)\left|\frac{\int_o^z K(z)dz}{\sigma^2}\right|$$

where $K(z)$ depends only on the distance z from the central plane of the disk and the velocity component in this direction, denoted as W. The relation between an observed density and a velocity distribution of stars will depend on the gravitational field and on whether the system is in dynamical equilibrium. If this equilibrium is evident either from the observations themselves or from theoretical considerations, then a steady state condition is satisfied. The theory of stellar dynamics may serve to derive the gravitational field and, therefore, to determine the mass distribution in the system. In the distribution function used by Oort (1932), the so-called Liouville's theorem of equation of continuity, $Df/Dt=0$, and Poisson's equation of gravitational potential $v_0=4$ Gp were adopted and solved them independently. The equation of continuity requires that the number of stars or gaseous material moving into the six dimensions of phase space dx, dy, dz, dU, dV and dW (where x, y, z are coordinates and U, V, W are space velocities) in a time (Dt) and those moving out of it in the same must be equal. In other words, no new stars are created and no stars are destroyed in a volume element $D(f)$ and time $D(t)$ (Oort, 1965).

In recent years two new methods of analyzing tracer data have been proposed

(Bahcall 1984a, b and c; Kuijken and Gilmore 1989). These two proposed methods of tracer analysis are different in approach. On the one hand, Bahcall's method compares the observed tracer density profile to various trial density profiles, each corresponding to a particular trial potential and solves both the Poisson equation, $v_0 = 4$ G [p(disk) + p (halo)] and the first moment of the Boltzmann equation, that describe the motion of an isothermal population of stars perpendicular to an axisymmetric galactic disk simultaneously. In Bahcall's method, the solution depends upon the ratio of the effective halo mass density to the disk mass density in the plane of the disk.

Kuijken and Gilmore (1989), on the other hand, have proposed a much simpler technique. They concentrate on determining the linear term in the high altitude potential, using high-latitude tracers, thus, a specific population of star at the galactic poles. This term is proportional to the column density of the disk. This measured column density may then be related to what the column density would be if there were no missing mass.

In Bahcall's case, the determination of a distribution function and a gravitational potential is based on the joint solution of the Boltzmann and Poisson equations (Bahcall 1984a, b, c). The total mass density in the solar neighborhood is found to equal $0.185 + 0.02 M_{\odot}/\mathrm{pc}^3$ according to Bahcall. A dynamic determination of the local mass density using A and F-stars in the region of the North Galactic Pole, based on radial velocities and photometric data (Hill, Hilditch and Barnes 1979; hereafter referred as HHB) and a theoretical model due to Camm (1950, 1952) yield a value of $0.14 M_{\odot}/\mathrm{pc}^3$. The total mass density of known matter in the solar neighborhood is found to be $0.108 M_{\odot}/\mathrm{pc}^3$ by HHB. However, Bahcall (1984b) has pointed out that HHB's mass density requires a small but uncertain correction due to the existence of binaries (Bahcall et al, 1985). Therefore, there is no large difference between HHB and Bahcall's results.

Using a bimodal initial mass function, Larson (1985, and 1986) has suggested that all the unseen mass in the solar neighborhood can be attributed to remnants of early generations of massive stars. In such a model, the formation of low-mass stars does not occur until the residual gas has settled into a disk. This disk would then be a secondary system formed partly of matter recycled from halo stars as proposed by Ostriker and Thuan (1985).

Regardless of what methods of stellar dynamics are used, a specific type or population of stars to a z-distance of 1.5kpc is necessary for the investigation of velocity dispersion. In the presently available data, little information is known to a z-distance beyond one kpc for large numbers of unevolved main sequence F-stars.

In the first large scale attempt by Oort (1932) about 50 years ago, he was partially successful in defining the galactic force law analytically. More recent works have been carried out by Hill (1960) and Oort (1960). The sample of stars available for Oort's work was small and consisted of inhomogeneous groups of old disk stars. It is remarkable that Oort was able to draw such fundamentally sound conclusions from such fragmentary data. Since the time of Oort's study, a great deal of observational material has been gathered concerning the kinematics and physical properties of the high-velocity stars by Fricke (1949), Eggen (1962, 1964) and Sandage (1969).

Solutions for the $K(z)$ force have usually had to be based on the giants because they are luminous and relatively abundant at high galactic latitudes (Upgren, 1962,1963; Turon-Lacarrieu, 1971; Dessureau and Upgren 1975; Hartkopf and Yoss 1982). However, the absolute magnitudes of the late-type giants including M-stars (Jones, 1962) appear to vary with z in a way that is difficult to measure with certainty, since they are evolved stars and are thus less homogeneous both chemically and kinematically.

Studies concerning early-type stars, including B and A stars,were those of Woolley (1957), Jones (1962), Woolley and Stewart (1967), and Perry (1969). These stars are luminous but their scarcity at large z-distances has hampered studies of the large-scale structure of the Galaxy. However, although faint K and M dwarfs are suitable, their absolute magnitudes are fainter than F-stars by 5 to 7 orders of magnitude. Therefore, large telescopes or an extensive medium telescopes time is required. Thus main-sequence F-stars would be more suitable than the giants or A-stars.

The advantages of using F-stars at the galactic poles as compared with any other stars have been pointed out by Upgren (1977), King (1983) and Freeman (1985). First, at high galactic latitudes, the density distribution of a group of stars in the z-direction related to its velocity distribution defined as W-velocity has less effect due to the rotation of the Galaxy. Second, F-stars are reasonably abundant (about 19 stars per square degree between 14 and 15th magnitude, Bok and Basinski, 1964 and about 49 stars per square degree between 10 to 16.5 magnitude, Lu, 1988), and would also be identifiable at great distance from the disk using an objective-prism with a dispersion of 1360 Å/mm (Blanco, 1974).

In a recent study shown by Gould (1989), that large sample of tracer objects is important to the statistical analysis, but the effectiveness of a survey deteriorates greatly the more the tracers deviate from being isothermal (Gould, 1989). In another word, a few hundred tracers are sufficient to determine whether the disk has a substantial quantity of missing matter.

The attempts at measuring $K(z)$ directly have never been very satisfactory. The primary reason for this lies in the shortage of radial velocity data for very faint and far distant stars in the direction of the galactic poles. The importance of obtaining radial velocities of very faint and distant stars has been pointed out by many investigators (Schmidt, 1965; Stock et al. 1977; Blaauw, 1978; King, 1983 and Freeman, 1985). The radial velocity of very faint F-stars is of a statistics in nature and vitally important for large scale galactic work, although high precision is not necessary. Thus, an average velocity accuracy of +/-5 km/sec for magnitude brighter than 16 is adequate for this purpose.

Currently, a few projects involving surveys of radial velocities of nearby dwarf A and F-stars are underway, notably those by Andersen and Nordstrom (1983a, b, c; 1985), Nordstrom and Andersen (1984), Hill et al (1979), and McFadzean et al (1982, 1987). Although a large-scale project, it would not provide the necessary data to study the large distance and thick disk problem, since these surveys have the limiting magnitude of about 9 or a distance of about 300 pc. All of Andersen and Nordstrom's stars were selected from the 4-color photometry of 4000 dwarf A and F stars brighter than 8.5 (Olsen, 1983). Other investigators are studying very distant field halo stars in order to determine the kinematics and metal abundance distribution in the outer regions of the galactic halo based on late giants (Dessureau and Upgren, 1975; Hartkopf and Yoss, 1982; Ratnatunga and Freeman, 1984; Andersen and Jensen, 1985). Although both luminous and numerous at large distances, they are evolved objects; thus their absolute magnitudes are uncertain at large z-distances.

2. OBSERVATIONS AND RESULTS

a. Curtis Schmidt Observations

Using a 1.5 degree prism with a dispersion of 1360Å/mm, Blanco (1974) has found that the prism allows the recognition of A4-G2 spectral types up to a photographic magnitude of 16.0. Although, detailed spectral classifications are not normally possible at this low dispersion, a broad range of spectral types are recognizable under good seeing condition. A similar low-dispersion survey of the northern sky with a 1.8 degree prism, which provided a dispersion of approximately 1500Å/mm centered at 4500Å, was carried-out by Pesch and Sanduleak (1983), and Sanduleak and Pesch (1984). With Eastman Kodak IIIa-J plates baked in forming gas, the plates reach a limiting magnitude of $B=18.0$ using a 75 minute exposure time.

Objective-prism plates centered at the South Galactic Pole have been obtained during December 14-22, 1987 and August 19-22, 1988 for the entire region of the 100 square degrees using the Michigan Curtis Schmidt telescope at CTIO. There are 9 objective-prism plates, and each has a 5×5 square-degree field, covering a total of 144 square-degree area. The overlap is about 50% at the central region where as the four corners have no overlapping (see Fig. 1). Both 15 and 90 minute exposure times were

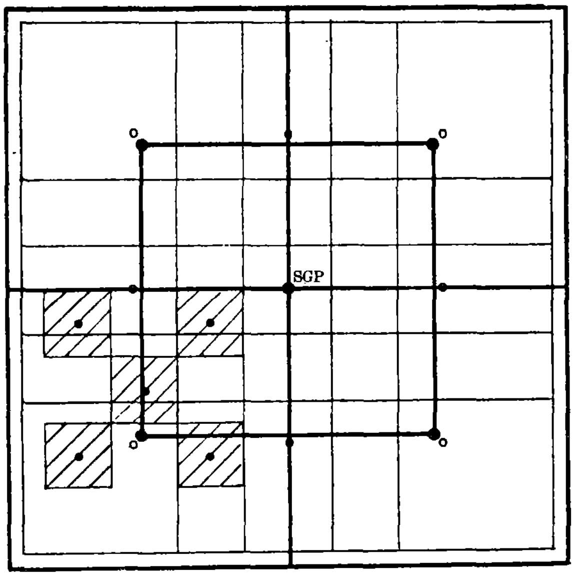

Fig.1 Objective-prism Survey for F-stars at the South Galactic Pole
Bold line: UK Schmidt, 5 plates cover 12.6 × 12.6 degree
Light line: Curtis Schmidt, 9 plates cover 12 × 12 degree
Hatched areas: Bok and Basinski Photographic Survey using B-V 5 plates cover 1.5 × 1.5 degree each
Plate Centers:
● UK Schmidt Plates
○ Curtis Schmidt Plates
• Bok and Basinski Plates

used for each region to insure that all stars within the magnitude range of 8.5 to 16 were properly exposed. Using the thin prism and baked IIIa-J emulsion, the plates can readily reach $B=16.5$ with 90 minute exposure time and the spectral types in the broad range are easily identifiable (Lu, 1988).

Objective-prism and direct film copies were also provided by the UK Schmidt Unit at the Royal Observatory, Edinburgh, Scotland. These films have superb quality of comparable dispersion and each film covers a 6.3 by 6.3 square-degree field. Since the films were obtained in the search for extragalactic objects at the SGP and have a limiting magnitude of 21 with a 70 minutes exposure time, stars brighter than 15th magnitude would be generally overexposed.

Direct plates with IIIa-J+GG385 and IIIa-F+GG495 were also made. Photographic V magnitudes and B-V colors will be deduced using the Yale PDS scan. This procedure is to ensure the completeness of the visual examination of the thin prism spectra for the F-type stars. The PDS scan using this procedure is in progress.

b. Direct CCD Photometry

In the case of the F-stars, the misidentification of a giant as a dwarf is not of great importance because there are very few F-type stars above the main sequence in this region of the HR diagram. However, a problem does exist with the F subdwarf stars of high ultraviolet excess. These old stars lie about a magnitude below the ZAMS, according to Sandage (1970), and can be expected to predominate in regions well away from the galactic plane. Distinguishing the subdwarfs from the normal dwarfs is difficult in objective-prism surveys. However, photometrically, it is possible to identify them from their luminosity and metallicity using 4-color and beta photometry.

Direct CCD photometry for 11 nights at the CTIO during December, 1987, August and November, 1988 for the newly identified F-stars were obtained using the 0.9m telescope with a RCA1 and a TI CCD chip at CTIO. Standard stars from Crawford (1975, 1979), and Twarog (1984) were selected and were also observed. The results show that it normally requires 4 to 5 minutes integration time to reach a 16th magnitude star in *vby* bandpasses. Since the RCA chips have very low quantum efficiency in the UV region, triple integrating times are needed in *u*-band to achieve the same intensity. A typical 2D-Frutti spectrum and a direct CCD frame are shown in Figures 2 and 3.

c. Radial Velocity Measurements

Methods have been developed (Fehrenbach and Burnage, 1981; Stock et al. 1977)

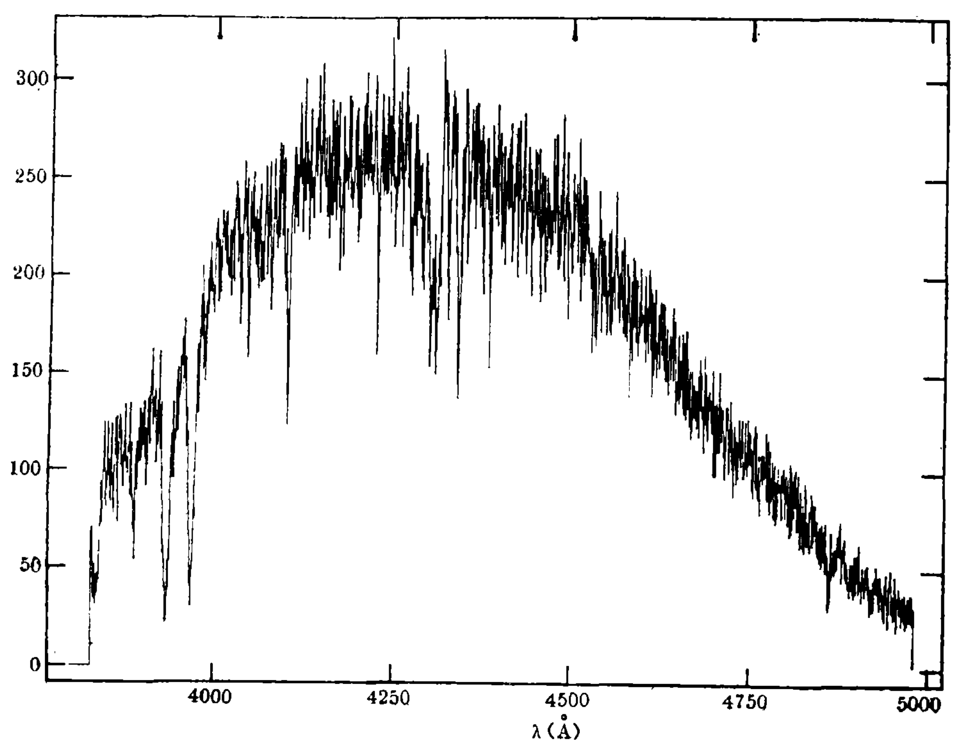

Fig.2 2D-Frutti Spectral Sample for a F9 Star

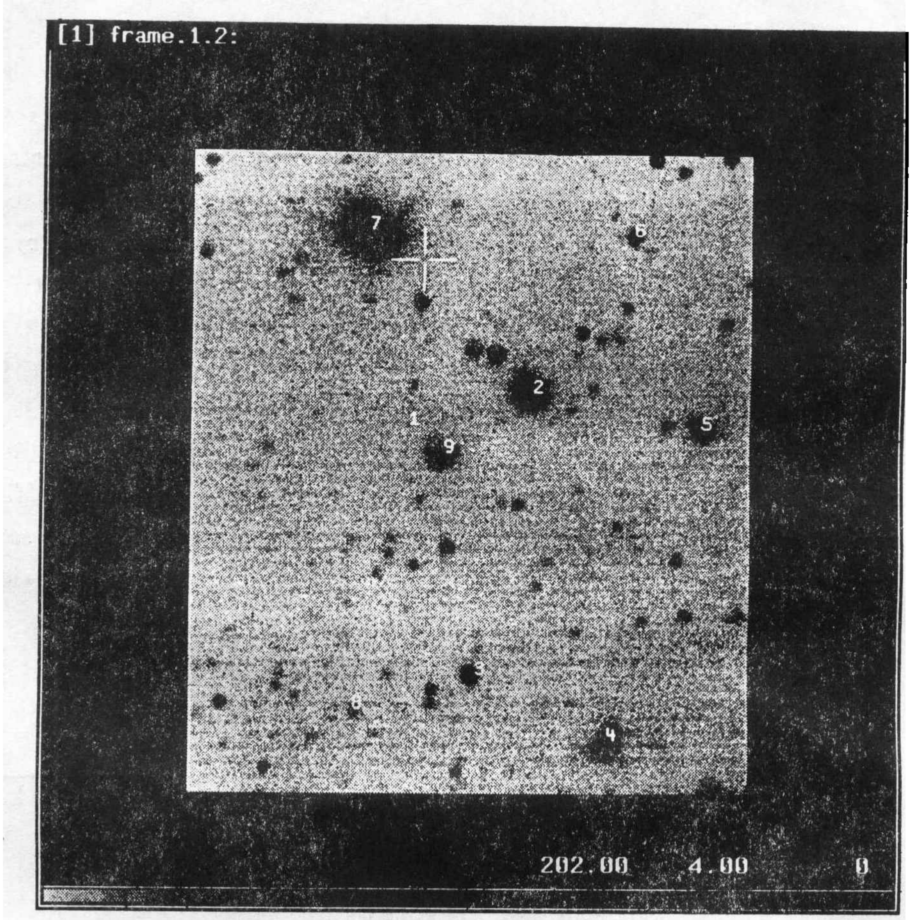

Fig.3 A Direct CCD (Charge Coupled Device) Picture Near The South Galactic Pole

to obtain the radial velocity using objective prisms with sufficient accuracy for statistical purposes. However, this study will use the more advanced instruments at CTIO to observe these F–stars to a distance of about 1.5 kpc. These instruments include a 2-dimensional photon detector, the 2D–Frutti system and a Multiple Object Fiber Feed Spectrograph, called ARGUS. It is possible to obtain spectroscopic and radial velocity using these same instruments. Radial velocity reduction using IRAF (Image Reduction and Analysis Facility) is also in progress. Spectra and calibrations are shown in Figs. 4 and 5.

All reductions will be carried out at the Center for Galactic Astronomy of WCSU using an AED (Advanced Electronic Display) model 767 and a Micro–VAX II computer linked with the university main frame VAX 11/780 and VAX 8550 computers. All CCD photometric reductions are conducted using the DAOPHOT program developed by Stetson (1987). A cross-correlation program will be used for radial velocity reductions. Some radial velocities for the southern stars have been reported by Lu(1983),

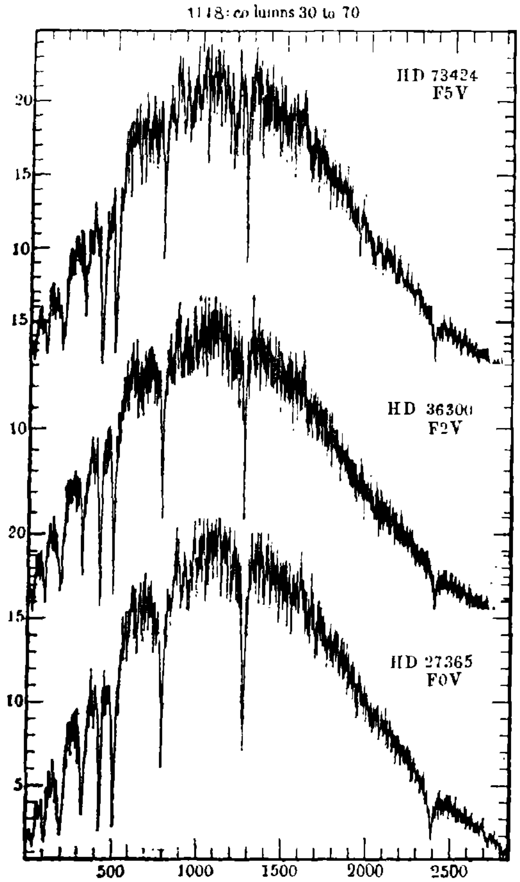

Fig. 4a　2D-Frutti MK Spectral Standards

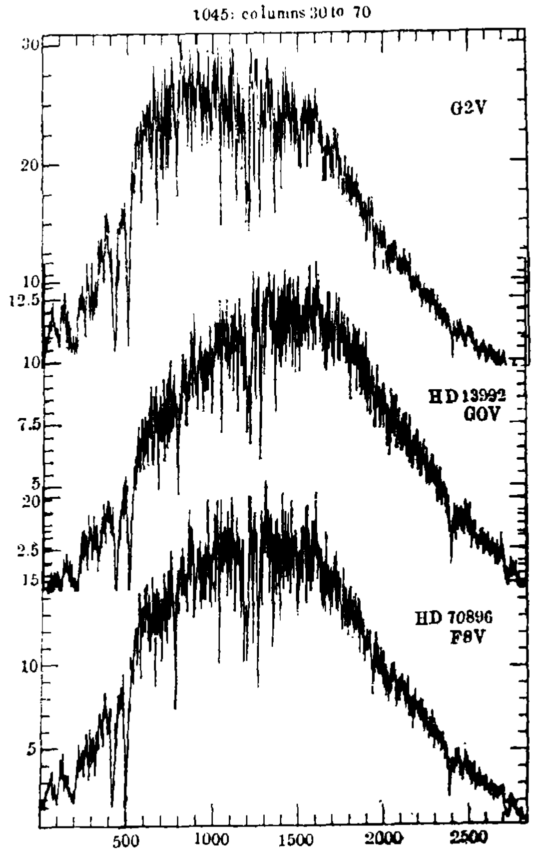

Fig. 4b　2D-Frutti MK Spectral Standards

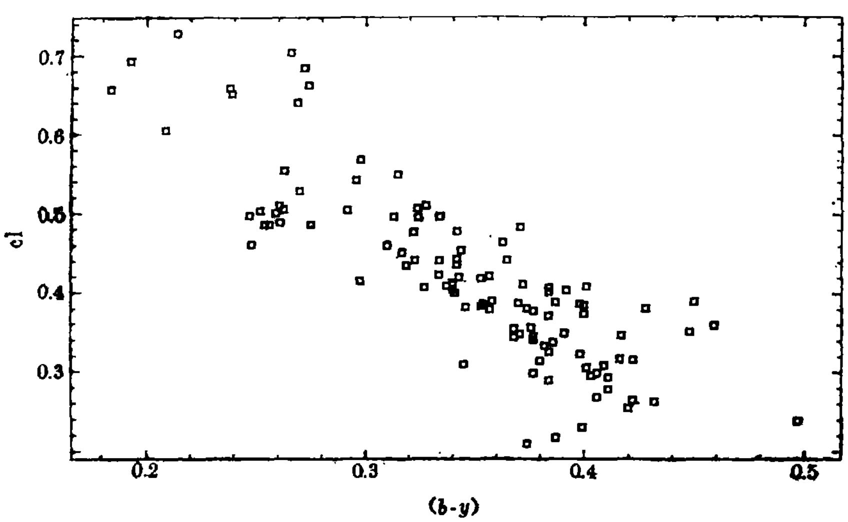

Fig. 5a　Four-Color Photometry for $(b-y)$ VS. c1

Lu and Lee(1983), Lu(1985) and Lu(1987) using this technique.

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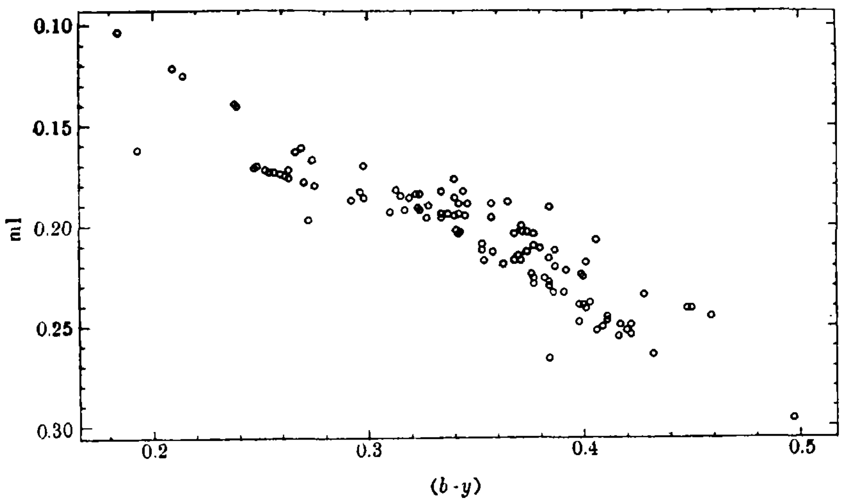

Fig. 5b Four-Color Photometry for (b-y) VS. ml

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银河系中的暗物质与短缺质量

吕 克 华

（西康涅迪克州立大学 威斯来茵大学，美国）

提 要

现在为决定银河系垂直盘面方向的引力 $K(z)$ 与局部质量密度方面，以暗主序F星为对象的研究正在获得进展，这一研究的主要目的在于探讨厚盘存在的证据及对银盘中短缺质量和暗物质进行动力学研究。

利用 UK Schmidt 胶卷与 Michigan Curtis Schmidt 底片，现在完成了以南银极为中心的100平方度范围内的物端棱镜的观测结果，使用色散度为 1360 Å/mm 的 1.5 度薄棱镜，经 III_a-J 乳胶处理及爆光90分钟，由此新的物端棱镜所得的光谱已产生出一组极限星等为16.5的均匀选择的F星。用直接的 *UVBY* CCD 光度测量和色散度为 43 Å/mm 的 2D-Frutti 系统的分光测量给出了一组必要的F型晕星，以此可以用来研究速度分布及短缺质量的动力学研究。