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STAR COUNTS AS AN INDICATOR OF GALACTIC STRUCTURE AND QUASAR EVOLUTION

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ABSTRACT

A detailed model of the stellar content of the Galaxy is described briefly. Illustrative applications of the model are made, using existing data, to indicate how star counts can be used to determine some parameters of galactic structure, to detect a massive (stellar) halo, and to constrain models of quasar evolution.

Subject headings: galaxies: Milky Way — galaxies: structure — quasars

I. INTRODUCTION

Automated methods have been used recently to detect, classify, and measure objects on deep photographic plates in order to obtain catalogs of galaxies to faint limiting magnitudes. Faint star counts have been derived as incidental by-products of these extragalactic studies (Kron 1978, 1980; Tyson and Jarvis 1979; Peterson *et al.* 1979; Brown 1979). We show that these new counts of faint stars, when combined with classical observations at brighter magnitudes (Seares *et al.* 1925), can be used to provide important information on such diverse topics as the structure of the disk and spheroid components of the Galaxy, the properties of a massive halo, and QSO evolution.

Our results are obtained with the aid of detailed models of the Galaxy which are described extensively in Bahcall and Soneira (1980; hereafter Paper I.) We limit ourselves here to some of the more significant results which have observational consequences and which illustrate the importance of faint star counts for a variety of applications. (Some of the topics that are discussed extensively in Paper I but are not considered here are B-band star counts, the effect of galactic obscuration, a comparison of the predictions of the Hubble and de Vaucouleurs spheroid density laws, the ellipticity of the spheroid, the spheroid luminosity function, approximate analytic formulae for the predicted star counts, the effects of various parameter variations on the star counts and the inferred properties of the Galaxy, and the best regions in which to observe in order to determine various parameters of galactic structure.)

II. GALAXY MODEL

The observed distribution of visible stars in spiral galaxies is described accurately (de Vaucouleurs 1959; Freeman 1970; Kormendy 1977) for most spirals by the combination of a thin exponential disk and a de Vaucouleurs spheroid which has a light distribution similar to that of an elliptical galaxy. Rotation curves of other galaxies imply the existence of a third, halo component (Oort 1965; Ostriker, Peebles, and Yahil 1974; Einasto, Kaasik, and Saar 1974). We adopt the following density distributions, which are suggested by the above-mentioned observations:

$$\rho_{\rm disk}(r) \propto \exp\left[-z/H(M) - (x - r_0)/h\right] , \quad (1a)$$

$$\rho_{\rm spheroid}(r) \propto (r/r_0)^{-7/8} \exp\left[-10.1(r/r_0)^{1/4}\right] , \quad (1b)$$

and

$$\rho_{\rm massive\ halo}(r) = \rho_H(r_0)[a^2 + r_0^2]/[a^2 + r^2] . \quad (1c)$$

Here z is the distance perpendicular to the galactic plane, x is the distance in the plane from the galactic center to the point of interest, $r^2 = z^2 + x^2$, $r_0 \approx 8$ kpc (the distance of the Sun from the galactic center), $h \approx 3.5$ kpc, and a is an adjustable constant. The disk scale heights $H(M)$ depend on absolute magnitude and are taken from observations (see Paper I for a discussion of the uncertainties in the above parameters and references to the original observational papers).

The luminosity functions for the disk and spheroid stars are taken from observations in the solar neighborhood (see especially McCuskey 1966 for the disk and Schmidt 1975 for the spheroid). We find that, to the accuracy of the available data, the two observed functions have the same shape over the range they have in common ($4 \leq M_V \leq 12$). The luminosity functions are measured, for both components, over the range of absolute magnitudes that are expected on the basis of our models to contribute most to the star counts for $m_V \leq 30$. The ratio of densities in the disk and spheroid components in the solar neighborhood is 800:1. The luminosity function of the halo is not known, but is constrained by the observations we discuss later.

The stellar luminosity functions and scale heights are assumed independent of distance from the galactic center. The spheroid is assumed to consist exclusively of high-velocity stars and hence is made up mostly of population II stars. The empirical model for the disk contains a broad range of stellar populations.

III. DISK AND SPHEROID STAR DISTRIBUTIONS

The expected disk and spheroid star distributions on the sky are calculated by integrating the products of the density and luminosity functions described earlier over the appropriate apparent magnitude range and over the volume within a specified solid angle. Some typical results for high galactic latitudes (50° and 90°) are shown in Figure 1*a*. The results plotted in Figure 1*a* for the differential star densities have been averaged over galactic longitude. The calculated and observed (see references in the figure legend) star densities are in excellent agreement in the well-studied range from $4 \leq m_V \leq 22$ in which the star densities vary by five orders of magnitude. The observations beyond $m_V = 22$, near the faint limit of detectability, are not yet all in agreement with each other, perhaps because of contamination by galaxies and other systematic errors (see Paper I for an extensive discussion of this point.)

The calculated star counts vary significantly with longitude; the dependence predicted by the model is in good agreement with all the available data. In Figure

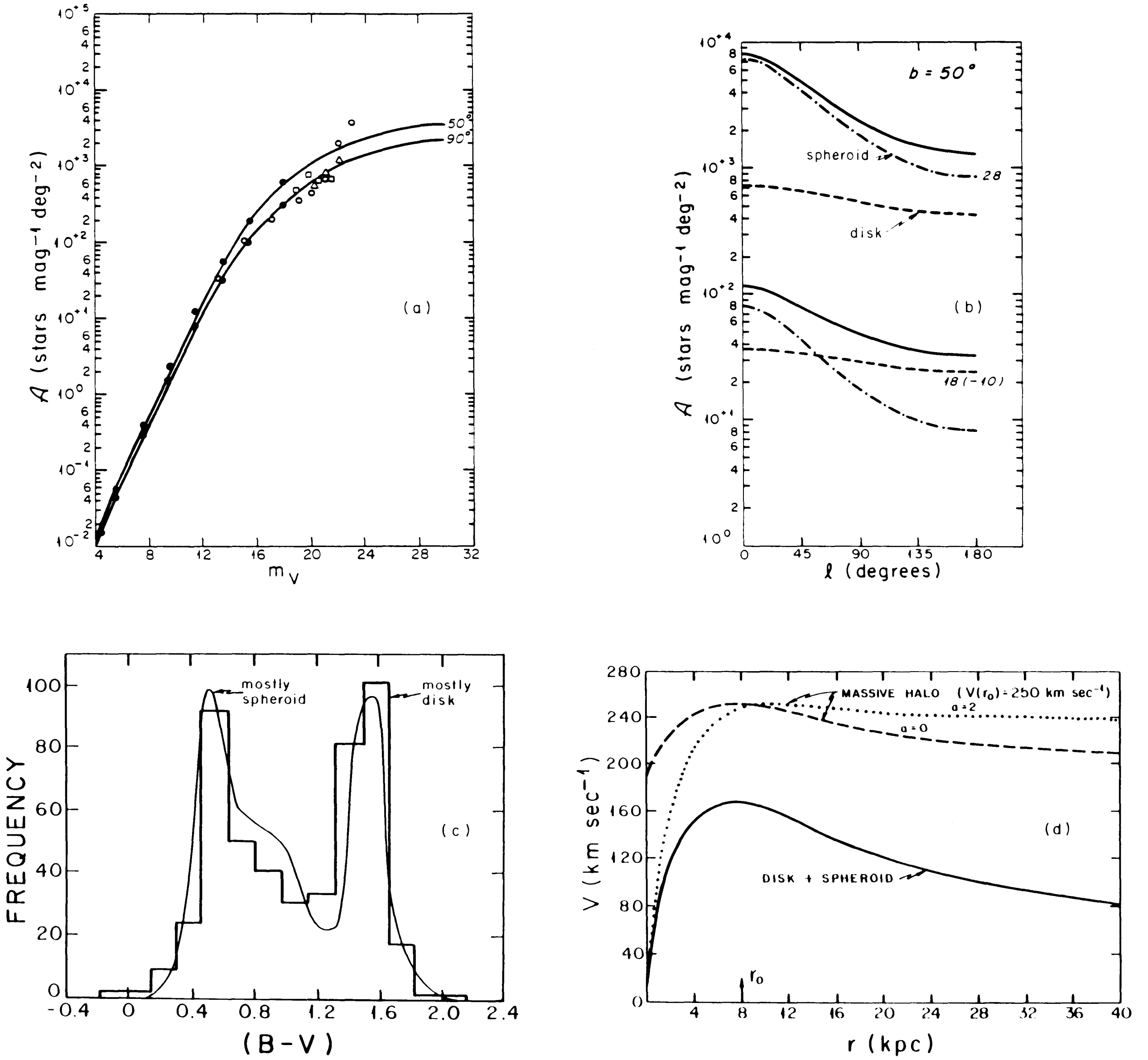

FIG. 1.—(*a*) Calculated differential star densities $\mathcal{A}$ per magnitude per square degree, averaged over longitude for latitudes *b* of 50° and 90°. Data from Seares *et al.* (1925) are plotted as filled circles. Data from Kron (1978) are plotted as triangles, data from Tyson and Jarvis (1979) as open circles, and data from Peterson *et al.* (1979) as squares. (*b*) The variation of calculated differential star densities $\mathcal{A}$ with longitude for $b = 50°$ and magnitudes 18 and 28. Contributions of the disk (*dashed lines*) and spheroid (mixed *dots* and *dashes*) to the total differential star densities (*solid lines*) are indicated separately. The star densities for 18th magnitude have been divided by a factor of 10 for convenience in display. (*c*) The distribution of $(B-V)$ colors in the direction of the galactic pole for stars with apparent visual magnitudes between 19.75 and 22.0. The smooth curve shown is the distribution predicted by the Galaxy model. Data from Kron (1978) are plotted as a histogram. (*d*) The rotation curve in the plane of the disk for a two-component Galaxy model is shown as a solid line. Two illustrative models with massive halos defined by equation (1c) and the parameters indicated in the text are also shown.

1*b*, the calculated variation with longitude has been plotted separately for the disk and spheroid components at $b = 50°$. Most of the variation in the star densities with longitude is seen to arise from the spheroid. An observational determination of the longitudinal dependence of the differential star counts at $b = 50°$ would be important in improving the accuracy with which the spheroid density normalization and ellipticity are known (see Paper I for a list of optimal directions).

The calculated differential counts are dominated at the galactic pole by the disk component for $m_V \lesssim 16$ and by the spheroidal component for $m_V \gtrsim 19$; the disk and spheroidal densities are equal at 17th magnitude. (For the integral counts, the corresponding values are about two magnitudes dimmer.) At a latitude of 20°, the counts averaged over longitude remain dominated by disk stars about four magnitudes fainter than at the galactic pole.

The predicted distribution of $B - V$ colors for stars in a given apparent magnitude range can be calculated from the Galaxy model. The model color distribution is compared in Figure 1*c* with the observations of Kron (1978) for stars in SA 57 ($b = 86°$). The agreement between the calculated results and the data is excellent.

A double-peaked distribution in $B - V$ that separates disk and spheroid stars is apparent in Figure 1*c*. Almost all (>85%) the stars with $B - V > 1.2$ are in the disk, and almost all (>99%) the stars with $B - V < 1.2$ are in the spheroid. The disk stars in a magnitude-limited sample near the pole are *redder* than the spheroid stars in spite of the fact that color distributions for the components are assumed to be the same in space. The density gradient is much steeper for disk stars in this direction, so that at faint magnitudes one predominantly observes intrinsically faint (red) stars. The distribution of $B - V$ colors has two conspicuous peaks throughout the magnitude range $18 \lesssim m_V \lesssim 24$ and for directions well outside the galactic plane.

The principal calculated characteristics of the two visible components of the Galaxy are summarized in Table 1. (These estimates depend sensitively on the scale length h in the disk.) In addition, the surface densities for the disk at the solar position are 16 $L_\odot$ pc^{-2}, 27$\mathfrak{M}_\odot$ pc^{-2}, and 95 stars brighter than $M_V = +19$ pc^{-2}. The results given here are in good agreement with observations of our Galaxy and other galaxies (see Paper I for a detailed discussion).

IV. LIMIT ON THE QUASAR NUMBER DENSITY

The agreement between the $(B - V)$ distribution predicted by the model Galaxy and the observed (Kron 1978) distribution of colors of faint stellar objects places a severe constraint on the evolution of QSOs. Only 2% of the stellar objects in Kron's sample to $m_V = 22$ have $(B - V)$ colors bluer than 0.30 mag. Assuming that about 60% of the QSOs with $m_V \lesssim 22$ have $(B - V) \lesssim 0.30$ (see the catalog of identified quasars by Burbidge, Crowne, and Smith 1977), then the observed number density of QSOs brighter than $m_V = 22$ mag ($m_B = 22.5$ mag) must be $\lesssim 65$ deg^{-2}. Moreover, the Galaxy model predicts the number density of white dwarfs with $B - V \lesssim 0.3$ to be about 10 deg^{-2}. Hence the number of QSOs brighter than $m_V = 22$ ($m_B = 22.5$ mag) is $\lesssim 50$ deg^{-2}, provided the QSO color distribution does not change radically with apparent magnitude. This is between one and two orders of magnitude smaller than the number density predicted by the extrapolation of the observed number-magnitude relation of QSOs between $m_V \sim 16$ and $m_V \sim 19$ (Steppe, Veron, and Veron 1979; Bohuski and Weedman 1979). The constraint stated above is not much larger than the number density of confirmed QSOs (~13 deg^{-2}, from an incomplete list to $m_B = 21$) in the sample of Hoag and Smith (1977). These results suggest that strong luminosity-dependent evolution may have occurred at an early epoch ($Z \gtrsim 3$), since otherwise the broad intrinsic luminosity function observed at smaller Z would have spread out evolutionary effects over an observed range of several apparent magnitudes.

V. A MASSIVE HALO

The rotation curve predicted by the Galaxy model with just disk and spheroid components is shown in Figure 1*d* for typical parameters. The maximum rotation velocity is less than 200 km s^{-1} and, for all the two-component models we have constructed, falls monotonically beyond 12 kpc. These results imply the existence of a third (halo) mass component for the Galaxy since other galaxies of the same morphological type have flat or slightly increasing rotation curves out to $\gtrsim 30$ kpc with a maximum rotational velocity ~235 km s^{-1} (see Rubin, Ford, and Thonnard 1978 and Bosma 1978, also Gunn, Knapp, and Tremaine 1979 and Blitz 1979, for a discussion of the rotation curve of the Galaxy).

The halo parameters (see eq. [1c]), $\rho_H(r_0)$ and a can be chosen so that the local rotation constants computed from the three-component model agree with the measured rotation constants and also so that the calculated rotation curve is approximately flat out to $\gtrsim 40$ kpc. Figure 1*d* shows two computed rotation curves that include a massive halo. The dashed curve corresponds to a halo with $\rho_H(r_0) = 0.011\ \mathfrak{M}_\odot$ pc^{-3} and $a = 0$ and the dotted line to a somewhat more massive halo with a larger scale length: $\rho_H(r_0) = 0.017\ \mathfrak{M}_\odot$ pc^{-3} and $a = 2$ kpc. The rotation constants for the halo with $a = 0$ are, for example; $A = 16.1$ km s^{-1} kpc^{-1}, $B = -15.4$ km s^{-1} kpc^{-1}, $Ar_0 = 130$ km s^{-1}, and a solar rotational velocity of 250 km s^{-1}.

The local halo density corresponds to ~10% of the total mass density in the solar neighborhood for the halo models discussed above. The total halo mass interior to the Sun's position ($r \leq r_0$) implied by the two model halos is about two-thirds of the total mass contained within r_0. These estimates of halo masses are sensitive to the assumed disk scale length ($h \sim 3.5$ kpc); they can be greatly reduced if $h \sim 2.75$ kpc (in which case very large values of a are possible).

Observed star counts (see Fig. 1*a*) can be used to place an upper limit on the intrinsic luminosity of

TABLE 1

SOME COMPUTED PROPERTIES OF THE TWO-COMPONENT GALAXY

Parameter	Disk	Spheroid	Disk + Spheroid
a) Solar Neighborhood			
Luminosity density ($L_\odot$ pc^{-3})	0.062	7.7 (−5)	0.062
Mass density of main-sequence stars ($\mathfrak{M}_\odot$ pc^{-3})	0.040	5.0 (−5)	0.040
Mass density of white dwarfs stars ($\mathfrak{M}_\odot$ pc^{-3})	0.005	6.3 (−6)	0.005
Star number density (stars pc^{-3}) for stars $M_V \leq +19$	0.15	1.9 (−4)	0.15
b) Total			
Luminosity ($L_\odot$)	1.2 (+10)	1.9 (+9)	1.4 (+10)
Mass of visible stars ($\mathfrak{M}_\odot$)	2.0 (+10)	1.4 (+9)	2.2 (+10)
Mass ($\mathfrak{M}_\odot$)[a]	5.6 (+10)	3.3 (+9)	6.0 (+10)
Mass enclosed within r_0 ($\mathfrak{M}_\odot$)[a]	3.7 (+10)	2.4 (+9)	4.0 (+10)
Number of stars ($M_V \leq +19$)	7.2 (+10)	4.6 (+9)	7.6 (+10)
Absolute visual magnitude (no obscuration)	−20.4	−18.4	−20.5
Radius enclosing 90% mass (kpc)	13	19	13
Escape velocity from galactic center (km s^{-1})	385	165	420
Escape velocity from Sun (km s^{-1})	255	55	260
Angular momentum ($\mathfrak{M}_\odot$ kpc^2 s^{-1})	1.9 (+3)	0	1.9 (+3)

[a] Local mass density of 0.15 $\mathfrak{M}_\odot$ pc^{-3} assumed. Interstellar matter of local density 0.045 $\mathfrak{M}_\odot$ pc^{-3} is assumed to be distributed like the visible stars in the disk but with a scale height of 125 pc. Remaining (dark) matter is assumed to be distributed like the visible stars in both disk and spheroid.

stars that might make up the massive halo. In an apparent-magnitude region in which halo stars are observed, the star counts should increase approximately as $10^{0.6m}$; this rapid increase is not observed in the data. Available observations constrain halo stars to have $M_V \gtrsim 14.0$ mag ($\mathfrak{M} \lesssim 0.15\ \mathfrak{M}_\odot$, spectral type later than M6) if they are main-sequence stars and $M_V \gtrsim 13.0$ mag for white dwarfs. This implies $(M/L)_{\rm halo} \gtrsim 650$ (solar visual units). Space telescope observations at $m_V = 28$ will reveal the stellar constituents of a massive halo if the halo consists of main-sequence–type stars with $M_V \lesssim 19.0$ mag or white dwarfs with $M_V \lesssim 17.5$ mag.

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