KITT PEAK, Bright Galaxies, and Dark Matter

KITT PEAK NATIONAL OBSERVATORY
17 March 2010
Vera at Kitt Peak 84-
Vera and DTM
Kent surprised Vera as she came to 84-inch catwalk to view (cloudy) sky, 1980s.
Andromeda Nebula

Al Sufi, 10th Century Persia
GALELIO 1564-1642
f.116v, on which Galileo first noted the parabolic path of horizontally launched projectiles. Manoscritti Galileiani in the Biblioteca Nazionale Centrale di Firenze (reproduced by permission).
ISAAC NEWTON 1642-1727
PHILOSOPHIAE NATURALIS
astronomos universos. Magnitudines autem orbium Keplerus & Bullialdus omnium diligentissimè ex observationibus determinaverunt; & distantiae mediocres, quæ temporibus periodicis respondent, non differunt sensibiliter à distantibus quas illi invennerunt, suntque inter ipsas ut plurimum intermedia; uti in tabulâ sequente videre licet.

Planetarum ac telluris tempora periodica circa solem respectu fixarum, in diebus & partibus decimalibus diei.

\[ \begin{array}{ccccccc}
\text{H} & \text{d} & \text{m} & \text{s} & \text{f} & \text{f} & \\
10759,275 & 4332,514 & 686,9785 & 365,2565 & 224,56176 & 87,9692 & \\
\end{array} \]

Planetarum ac telluris distantiae \( u \) mediocres à sole.

\[ \begin{array}{ccccccc}
\text{Secundum Keplerum} & 951000 & 519650 & 152350 & 100000 & 72400 & 38806, \\
Secundum Bullialdum & 954198 & 522520 & 152350 & 100000 & 72398 & 38583, \\
Secundum tempora periodica & 954006 & 520096 & 152369 & 100000 & 72333 & 38710 & \\
\end{array} \]
(3) For 888 stars, the rotational velocity component about the center of the galaxy has been computed, and a mean curve derived (Fig. 5). Toward the center of the galaxy, the computed curve lies about 15 km/sec above the radio rotation curve (Schmidt 1956). For $R > 8 \, \text{kpc}$, the rotation curve is approximately flat. The decrease in rotational velocity expected for Keplerian orbits is not found. It is shown that systematic observational errors will not account for the shape of the curve.
Mt. Nucleus

Ref to w.r.t. em region

NS [N to SW] [W to SW] EW

\[ \sqrt{38 + 39} \left\{ \begin{array}{c}
38 \\text{°} 126^\circ \\
39 \\text{°} 122^\circ
\end{array} \right. \\
9.2 W \\
4.4 S \\
0.25 S \\
10.8 S \\
16.6 N
\]

EW x F

NS x F

NS

100 15.14
9986.47
28.70
00028.76

1 \rightarrow 2

mean 1 \rightarrow 2 = a

F = \frac{a}{46.0} = \frac{28.73}{46.0} = 0.624

16
29.7 S
27.5 W
2.1 S

18.5
145.2

9981.50
9954.8

+ 17.15
- 45.2
M31
Rubin and Ford
from Baade 1944–1947
Rubin and Ford 1970

![Graph showing rotational velocity vs. distance to center in arc minutes. The graph includes data points for different regions (CENTER, SW, NE) and is labeled with M 31 and rotational velocity in km s⁻¹.]
Roberts and Whitehurst 1975

M 31

ROTATIONAL VELOCITY (km s⁻¹)

DISTANCE TO CENTER (ARC MINUTES)

OPTICAL

CENTER
SW
NE

From Rubin and Ford (1970)
Distance from nucleus $r$

Need velocities from largest $r$
Ratio dark/luminous increases with $r$
Rotverschiebung extragalaktischer Nebel.

Scheinbare Geschwindigkeiten im Comahaufen.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>$v = 8500$ km/sec</td>
<td>$6900$ km/sec</td>
</tr>
<tr>
<td>7900</td>
<td>6700</td>
</tr>
<tr>
<td>7600</td>
<td>6600</td>
</tr>
<tr>
<td>7000</td>
<td>5100 (?)</td>
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</tbody>
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Zwicky, 1933
DARK MATTER

DOES IT EXIST?  YES (Newtonian gravitational theory)
  rotation curves of galaxies
  galaxy motions in clusters of galaxies
  gravitational lensing

WHERE IS IT?

HOW MUCH IS THERE?

WHAT IS IT?

DOES IT EXIST?  NO (MOdified Newtonian Dynamics, MOND)
Virgo Cluster

NGC 4550

M87
CAN SPHERICAL CLUSTERS ROTATE?

D. Lynden-Bell

Summary

It is shown that contrary to former belief an unrelaxed spherical cluster of mass points may rotate without becoming oblate. When used of an unrelaxed system the argument that spherical objects do not rotate is thus false. Some present estimates of the Sun’s circular velocity round the galaxy rest on this argument applied to the system of globular clusters.

Introduction.—We are here discussing clusters of gravitating mass points. Thus applications may be considered at several levels.

(i) Clusters of galaxies.
(ii) To galaxies themselves.
(iii) The system of globular clusters centred on the galactic centre.
(iv) The globular clusters themselves.

The system of globular clusters shows no pronounced flattening at the galactic poles; is this good evidence that it does not rotate? If it is not, then the justification for the determination of the Sun’s circular velocity from the Doppler motions of the globular clusters is destroyed. These observations give the Sun’s velocity in the coordinates in which the system of globular clusters does not rotate, and we have no longer any justification for assuming that this is not a rotating coordinate system.

Consider a mighty Maxwell demon whose job it is to reverse the directions of motion of stars so that they describe their orbits in the reverse sense. We shall assume him capable of violating the law of angular momentum conservation. On his entering a non-rotating spherical star cluster let him pick a direction and a sense of rotation about it. Let him reverse the velocities of all those stars which do not have the picked sense of motion about this axis. It seems likely that he can do this without disturbing the formerly spherical density distribution. If this is the case he succeeds in making a spherical but rotating cluster. The assumption implicitly made is that any non-rotating spherical cluster may be considered as two inter-penetrating clusters, rotating in opposite senses, each of which is itself spherical. (It is clear that they cannot be flattened since then the complete
SOME FLATTENED ISOTHERMAL MODELS OF GALAXIES

ALAR TOOMRE
Department of Mathematics, Massachusetts Institute of Technology
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ABSTRACT

A family of exactly self-gravitating, collisionless stellar systems with axial symmetry is presented. Each model exhibits quasi-Gaussian random motions that vary not at all with distance along any given ray from its center, and the circular speed in its equatorial plane is likewise independent of the radius. In essence, these models thicken the infinitesimally thin Zang disks to include the classical sech² plane-parallel solutions of Spitzer and Camm; the surprise here is that such alterations remain exact to arbitrary thicknesses.

Two-component versions of these scale-free models yield some instructive disk-halo systems, including the ones proposed lately by Richstone and Miller. Their shapes and velocity fields are described in some detail.

Subject headings: galaxies: internal motions — galaxies: structure — stars: stellar dynamics

I. INTRODUCTION

The galaxy models about to be displayed here belong perhaps only in the category of elegant curiosities. At least that is how they have long seemed to this writer, who stumbled upon them in 1970 (after being urged by

\[ \langle V \rangle / \sigma = 0.80, \ 1.01, \text{ and } 1.35 \] for these unidirectional \( n = \frac{1}{2}, 1, \text{ and } 2 \) models would indeed be much too large for the typical observed ellipticals. However, as stressed by Figure 6d, beware again of simply reversing the velocities \( v_\phi \) for half the stars: In that case, not only would the equatorial \( \langle V \rangle = 0 \), but the major-axis dispersion would now equal 0.707 \( V_0 \) in all cases. This rms dispersion would exceed the minor-axis value only by the factors 1.22, 1.41, and 1.73. At least for the counter-rotating \( n = \frac{1}{2} \) model, it would require considerable care to notice, let alone measure, such anisotropy in practice.

Figure 7 repeats all these exercises in the equatorial planes of the first three composite models pictured in

Hence, the above reference density \( \rho_0 \) can be regarded simply as the mean value of \( \rho \) averaged over the surface of the sphere \( r = r_0 \), or as one-third of the average over its volume.

These density laws are, of course, nicely shape insensitive. But their nonrotation, to say nothing
Dear Vera,

Thanks for the reprints.

The paper on NGC 4550 reminds me that my student Araki at one time looked for evidence of a two-stream instability in counter-rotating stellar disks (paper enclosed). You'll be reassured to know that the counterrotating disks are more stable than an equivalent unidirectional disk.

I also enjoyed your paper on anticenter OB stars. I enclose a recent paper with Kuijken on large-scale oscillations. We point out (p 24) that measurements of the mean radial velocity of anticenter stars are important for looking for oscillations, and that the Blitz-Sprung model predicts -11 km s\(^{-1}\) for \(\bar{V}\) -- in contradiction to your data, which we had not been aware of.

Best wishes,

Scott
Gravitas: Dubinski & Farah
The Character of Physical Law
Richard Feynman

The Law of Gravitation, an example of Physical Law

In this lecture I would like to emphasize, just at the end, some characteristics that gravity has in common with the other laws that we mentioned as we passed along. First, it is mathematical in its expression; the others are that way too. Second, it is not exact; Einstein had to modify it, and we know it is not quite right yet, because we have still to put the quantum theory in. That is the same with all our other laws - they are not exact. There is always an edge of mystery, always a place where we have some fiddling around to do yet. This may or may not be a property of Nature, but it certainly is common to all the laws as we know them today. It may be only a lack of knowledge.

But the most impressive fact is that gravity is simple. It is simple to state the principles completely and not have left any vagueness for anybody to change the ideas of the law. It is simple, and therefore it is beautiful. It is simple in its pattern. I do not mean it is simple in its action - the motions of the various planets and the perturbations of one on the other can be quite complicated to work out, and to follow how all those stars in a globular cluster move is quite beyond our ability. It is complicated in its actions, but the basic pattern or the system beneath the whole thing is simple. This is common to all our laws; they all turn out to be simple things, although complex in their actual actions.

Finally comes the universality of the gravitational law, and the fact that it extends over such enormous distances that Newton, in his mind, worrying about the solar system, was able to predict what would happen in an experiment of Cavendish, where Cavendish’s little model of the solar system, two balls attracting, has to be expanded ten million million times to become the solar system. Then ten million million times larger again we find galaxies attracting each other by exactly the same law. Nature uses only the longest threads to weave her patterns, so each small piece of her fabric reveals the organization of the entire tapestry.