ON THE MAGELLANIC STREAM, THE MASS OF THE GALAXY AND THE AGE OF
THE UNIVERSE

D. Lynden-Bell
Institute of Astronomy,
The Observatories,
Cambridge CB3 OHA, England.

The Magellanic stream has been fitted with high accuracy in both
position and velocity by the tidal tearing of a Magellanic Cloud. To
get the good fit to the high velocity at the stream's tip at a suitable
distance from the Galaxy we need either a large mass for the Galaxy, or
a large circular velocity for the Sun, or both. An extragalactic
method of determining the circular velocity yields the high value of
$V_c = 294 \overset{+}{-} 42$ km/sec and an orbit of poor accuracy for the relative
motion of the Galaxy and the Andromeda nebula. Very large masses are
needed if Andromeda and the Galaxy were formed together. A new direct
determination of Hubble's constant from the "superluminal" expansion
observed in VLB radio sources gives an age of the Universe of 9 billion
years. Either larger masses still or smaller distances within the
local group are necessary to bring Andromeda back towards us in so short
a time.

Discovery of optical objects lying in the direction of the Magellanic
Stream and other hydrogen clouds[1] stimulated my interest in explaining
the stream. Work by Hartwick and Sargent[2] has since shown that the
apparent coincidences are caused by projection since the velocities of
the optical objects differ from those of the hydrogen. Nevertheless
over the intervening years D.N.C. Lin and I have run some forty thousand
test particle orbits comprising 200 passages of a Magellanic Cloud
clothed with 200 test particles[3]. Typically we start our Magellanic
Cloud at apo-galacticon with its rotation inclined at some specified
angle to the plane of the Magellanic Cloud's orbit. As our Magellanic
Cloud sweeps past perigalacticon and on, it is tidally torn making a
bridge towards the Galaxy and a tail away from it. We have discovered
orbits which give a tail and no bridge and others that give bridges
without tails. We have been at pains to fit the rather straight run
of velocity with angle around the sky which is observed in the Magellanic
Stream. We find this straightness to be a characteristic of orbits
that are somewhat retrograde in the sense that the spin of the Magellanic
Cloud has an inclination of 110° to 130° to its orbital angular momentum
about the Galaxy. A description of the orbits searched over can be
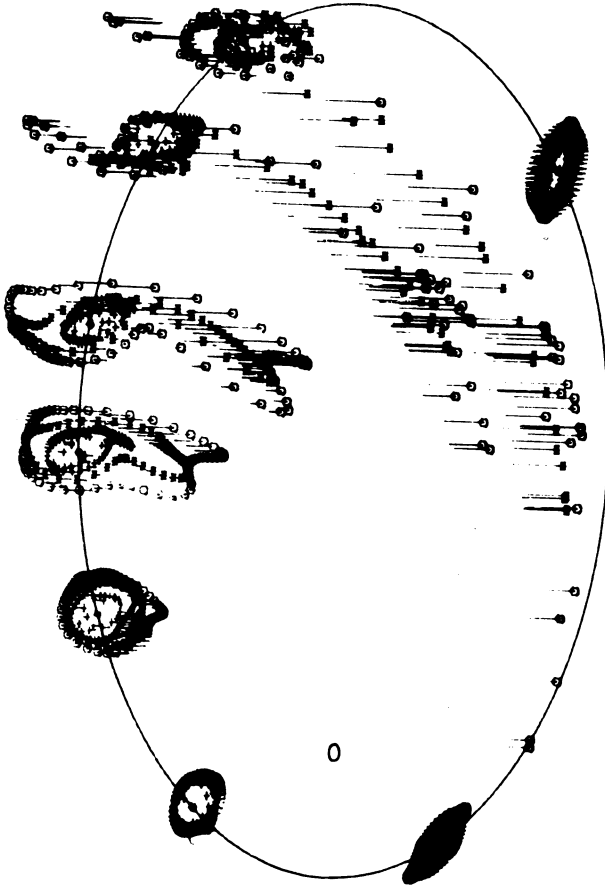found in our paper. We search in dimensionless units and when we

Figure 1. Our best fitting orbit for the Magellanic Cloud about the Galaxy. The small orbit of The Milky Way is seen near the focus. Picture is taken from an angle 30° above the orbit plane and the distance of point of the stream from that orbit plane are indicated. The orbit has $e = 0.7$, $i = 130^o$, $\mu_M = 1/50$, $P = 110^o$.

finally find an eccentricity e, a mass ratio μ_M, a Magellanic Cloud
size r, an inclination i and a direction of spin at apogalacticon P
that can scale exactly onto the observations, we determine the length
and velocity scales.   Using Newton's gravitational constant G, we can
then determine the mass of the Galaxy.   We found that such a fit was
not unique unless a circular velocity for the Sun's motion around the
Galaxy was first specified; however a single best fit configuration did
well in all cases if the velocity scale (and therefore mass scale) was
changed for each choice of circular velocity assumed.   (See Figure 1.)

To explain the high velocity of approach towards the Sun of the tip
of the Magellanic stream we need either a large velocity for the Sun
around the Galaxy so that there is less to explain in terms of infall,
or a large infall velocity.   A large infall velocity can arise either
because the tip of the stream has been pulled inwards by a very heavy
mass, or because the tip has fallen very deep into the Galaxy's potential.
We found that the almost great circle shape of the stream was spoiled by
parallax if the tip of the stream was too close to the Galaxy.   We
could not fit our best model to the positions of the stream on the sky
if the tip was closer than about 16 kpc from the galactic centre.(Davies
and Wright[4] have assumed that the stream's tip is a factor of two
closer.)   For the following circular velocities we get the following
masses for the Galaxy:

V_c/km/sec	300	290	250
$M_G/M_\odot$	$3.8.10^{11}$	$4.3.10^{11}$	$7.6.10^{11}$

It is evident that unless the circular velocity is very large, then the
Galaxy must have a heavy halo.   This result turned our interest towards
the value of the circular velocity.

The radial velocities of the galaxies in the local group reflect
the motion of the observer which is the compound of the motion of our
galaxy with the Sun's motion within it.   It has always been assumed
that these two velocities cannot be separated by extra-galactic measure-
ments so that the speed of the Sun's circular motion about the galaxy
V_c cannot be determined this way.   However this is false.   First
determine the Sun's motion, $\underline{U}$, with respect to the galaxies of the local
group excluding the Andromeda subgroup.   Assuming these minor galaxies
define the same zero of velocity as the centre of mass of the Galaxy
and Andromeda, the momenta of the Galaxy and Andromeda must be equal
and opposite.   Thus if $\underline{G}$ is the galaxy's velocity, Andromeda's will be
$-\mu\underline{G}$, where μ is the mass ratio M_G/M_A.   The observed radial velocity of
Andromeda will therefore be

$$v_{Ar} = (-\mu\ \underline{G}-\underline{U})\hat{\underline{r}}_A = (-\mu(\underline{U} - V_c\hat{\underline{c}}) -\underline{U}).\hat{\underline{r}}_A$$

where $\hat{\underline{c}}$ is the direction of the circular motion and $\hat{\underline{r}}_A$ is unit vector
towards Andromeda, from which we may deduce

$$V_c = (v_{Ar} + (1 + \mu)\underline{U}.\hat{\underline{c}})/(\mu \, \hat{\underline{c}}.\underline{r}_A)$$

Thus knowledge of the mass ratio μ yields V_c. Applying this method to
10 independent members of the local group yields V_c = 294 ± 42 km/sec
for the velocity of free circular motion at the Sun's distance from the
centre[5]. The dependence on μ has been removed by using the relation-
ship of Tully & Fisher[6] which gives the luminosity and thus the mass
of a spiral galaxy proportional to the 5/2 power of its maximum circle
velocity. With Andromeda's circular velocity at 265 km/sec the least
squares result is insensitive to μ in the range ½ to 1.25 and the most
probable result is always close to 290 km/sec.

This method yields not only V_c but also $\underline{U}$ and hence the Galaxy's
velocity $\underline{G} = \underline{U} - V_c \hat{\underline{c}}$ and Andromeda's velocity $-\mu\underline{G}$. With the aid of
these we can calculate orbits[5] for the galaxies about one another. The
total mass $M_A + M_G$ required to bring them close to one another
2×10^{10} years ago is > $1.3 \times 10^{12} M_{\odot}$. A smaller circular velocity will
yield a yet larger mass. My recent interpretation of "superluminal"
expansion in VLB gives directly a Hubble constant of 110 ± 10 km/sec/Mpc,
and a maximum timescale of only 9×10^9 years for the age of the
Universe[7,8]. Unless the distance to the Andromeda nebula has been
seriously over-estimated (by a factor of 1.5 or more) then the mass
needed to bring the two galaxies together in so short a time as 9×10^9
years will be of the order of $4 \times 10^{12} M_{\odot}$. However there is weak
evidence that other galaxies, Maffei I in particular, intervened to
complicate our naïve picture of binary dynamics.

The Age of the Universe

Figure 2 shows VLB observations[9] of the separation of components
in the radio galaxy 3C120. They were originally interpreted (using a
Hubble constant $H_{\circ}$ = 55 km/sec/Mpc) as a burst expanding at 5c followed
by another expanding at 8c. However, the rediscussion that follows
shows that a single expansion along the dotted line at 4.6c on that
scale, accompanied by a rebrightening of a "central" object is a better
interpretation. We picture the geometry involved as a flash of very
strong waves in a tube formed by an accretion vortex about a black hole.
This flash propagates both ways along the vortex tube and escapes as two
equal pulses of strong waves, each travelling outwards at the velocity
of light. The electric fields of each strong wave pulse accelerates
the electrons it encounters and causes them to radiate synchro-compton
radiation in the radio region. It is the regions currently exciting
electrons that are seen as radio bright. Although the material of the
sources is not moving rapidly outwards the excited patches move out with
the velocity of light. If the two pulses set out an an angle θ to the
line of sight, then the one moving towards the observer S_1 will move with
apparent lateral speed $\dfrac{c \sin \theta}{1 - \cos \theta}$ (1) with respect to central black hole O,
while the other source S_2 will move with apparent lateral speed $\dfrac{c \sin \theta}{1 + \cos \theta}$ (2)
The apparent lateral separation velocity of S_1 and S_2 will thus be
$v_s = \dfrac{2c}{\sin \theta}$ (3) while the ratio of the separations will be $\dfrac{1 - \cos \theta}{1 + \cos \theta}$. (4)
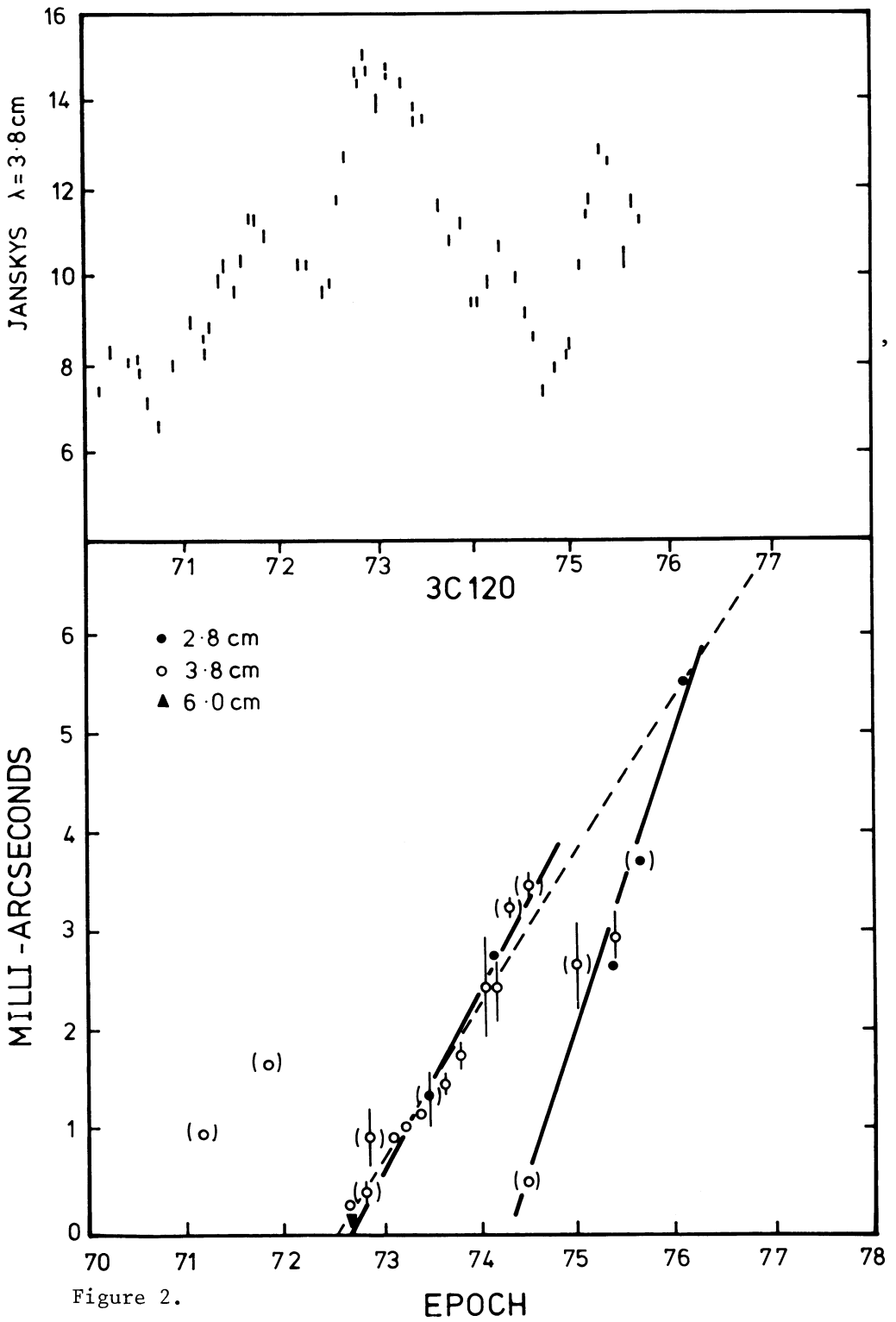
Figure 2.

Application to 3C120, z = .033

    Figure 2 shows the observations given in reference 10. The 3.8cm
flux shows an outburst in 1973 which caused a double source. This was
seen as a simple double expanding at about v_s = 5c (solid line) until
1974.2 when the double model failed to fit well, consequent upon a small
increase of flux. In 1975 there followed a violent increase of flux
and immediately a two source model fitted well again, but at about the
same separation as it was at 1974.0. The source began to dim in late
1975 and in 1976.1 it was again a well-determined double although the
flux at this time is not given. The authors of paper 10 have inter-
preted these events as the two superluminal expansions of 5c and 8c
given by the heavy straight lines. However on my picture this would
involve the vortex tube up the rotation axis of the radio galaxy to turn
between the two events and I consider this most unlikely, especially as
the observed position angle of separation on the sky are the same for
both doubles. The following interpretation of events is more natural
to me. 1972.5 - 1973 a double expanding source S_1, S_2 was born at O
and expanded throughout 1973 as its flux diminished. In early 1974
the object at O brightens, confusing the neat double interpretation of
the data. In 1975.2 O has increased in brightness so much that it forms
a double with S_1, the source moving towards us and S_2 is outshone and
ignored. O dims in late 1975 leading to a confused picture with S_1,
O and S_2 all seen. Finally in 1976 O dies away leaving the old expand-
ing source S_1 S_2. It is noted that this latest point fits on the dotted
expansion line (4.6c) of the old source, which is a perfectly good alter-
native to the full line (5c) if one ignores confused data. The peculiar
interest of this new interpretation arises because it not only removes
the discrepancy of two different superluminal velocities observed from
the same object, and therefore probably at the same θ but, because we
see O at times, we can measure the ratio of the separations OS_1 to OS_2
and hence <u>determine</u> θ. With θ determined, the apparent transverse
separation velocity is known from (3) so the observed angular velocity
gives the distance and hence Hubble's constant. The small z = 0.033
of 3C120 makes the cosmological corrections unimportant for this source,
so the Hubble constant derived in this case is independent of q_o.
However the same method applied to 3C345 should yield a reasonably good
value of q_o too.

    If θ were 90° the clear double seen in 1975.4 would have been half
way up to the dotted line. Its fractional offset $(OS_1 - \frac{1}{2}S_1 S_2)/S_1 S_2$
corresponds to the offset of O from the centre of S_1 and S_2 and is
therefore just $\frac{1}{2} \cos \theta$. From this we find $\theta = 68^o1 \pm 10^o$. It is
particularly interesting that this angle is close to the inclination of
the apparent disk of 3C120 measured from Arp's picture on which it appears
to be a disturbed spiral. Measuring his picture we get i = 55° - 60°
but this may well be in error by 10° due to the fact that the disturbed
disk does not have a circular outline. Furthermore the observed separa-
tion of the radio double, although fairly close to the apparent mirror
axis of the optical image is not along it. It seems reasonable to
assume that ejection is taking place along the rotation axis, but the

galaxy has imperfect circular symmetry.   As in such a case i should
equal θ and both determinations have similar errors we shall adopt
$\theta = 64 \pm 8^O$.   The light echo theory then gives us

$$v_s = 2c/\sin 64^O = 2.22c \pm 0.19c$$

The authors of reference 5 adopt H_o = 55km/sec/Mpc, and obtained 5c for
this velocity, but our correction to the dotted line interpretation of
Figure 2 yields 4.6c on that scale.   To get the answer deduced from the
light echo theory we must change the Hubble constant by a factor
$\frac{4.6 \pm .2}{2.22 \pm .19}$ = 2.1 $\pm$ 0.2.   We deduce a Hubble constant of 115$\pm$12km/sec/
Mpc.
Similar work on the 3C273 observations yields $\theta = 79^O$ and a Hubble
constant of 113^{+5}_{-10} km/sec/Mpc.   The statistics of the superluminal
expansions of $S_1 S_2$ for 3C120, 3C273 and 3C345 yields Ho=110$\pm$20km/sec/Mpc.
In summary this physical method of measuring H yields Ho=110$\pm$10km/sec/Mpc
and a maximum age of the Universe $H_o^{-1} = (9 \pm 1) \times 10^9$ years provided the
interpretation is correct.

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DISCUSSION

de Vaucouleurs: Do you believe that the spin axis of the accretion disk
in the black hole model coincides with the spin axis of the galactic
disk?

Lynden-Bell: If the system has been left alone without interaction for
a long time, then yes.

de Vaucouleurs: If so, does $\theta = 68^O$ agree with the inclination derived
from the shape of 3C 120?

Lynden-Bell: i = 55° - 60° ± 10°
                θ = 68° ± 10°
I think this is good agreement. I took θ = 64°.

THE STELLAR COMPONENT OF THE MAGELLANIC STREAM

William E. Kunkel

The problem of the Magellanic Stream (MS) is re-examined considering also stellar systems (globular clusters and dwarf spheroidal galaxies) lying between 25 and 250 kpc from the Galactic center (Kunkel and Demers 1976). The distribution of these systems is shown to be non-random, with a planar component whose inclination to the Local Group is 43°, and to the local supergalaxy exceeds 60°. The velocity distribution of members of the group shows a symmetry typical of debris associated with a disruptive event at perigalacticon of a victim moving in an elliptical orbit.

These data are examined in terms of tidal disruption affecting the Magellanic Cloud system, with a view to constraining the multidimensional character of admissible solutions from modelling efforts using computer simulation. The observed angle between the plane of the MS and that of the stellar or Magellanic Plane Group (MPG) is explained in terms of one being residue from a bridge and the other from a tail. The angle depends to a first approximation on only the mass ratio of the victim to the perturber, which is found to be 0.028, consistent with classical estimates for the masses of the LMC and the Galaxy.

Color-magnitude studies of the stellar systems, as well as the marked composition difference between the MS and the Magellanic Clouds point to a considerable age for the epoch of the most disruptive event, possibly just less than the age of the Galactic globular cluster system.

The sense of orbital motion (which also determines the status of bridge or tail) is determined independently from the age of the oldest (and most numerous) stellar component in the Wing of the Small Cloud, from the dominance of HI in the MS and of stars in the MPG, and from the uniformity (or its lack) of debris material in position along the debris orbits.

The model most favored by these arguments moves in a sense opposite to that of Davies and Wright (1977), and of Lin and Lynden-Bell (1977). The first encounter producing the most pronounced disruption (and much of the MPG and MS) occurred some time ago; the current position of the Magellanic Clouds near perigalacticon correspond to a second or possibly subsequent encounter with relatively mild interaction; the orbital period is of the order of 5×10^9 years. The total Galactic mass lying inside perigalacticon consistent with this model is a factor of 3 or 4 greater than the classical values in current use.