

OUR GALAXY

• SPIRAL GALAXY [NORMAL!]

~ 100 BILLION STARS

~ DISK $\approx$ 30,000 pc DIAMETER , 500 pc THICK
AT SUN

~ 'ALL' STARS + GAS IN DISK

+ 'DARK' MATTER

- DISK

- HALO + NUCLEUS

- BULGE

- 'CORONA'

INTERSTELLAR DUST

- ZONE OF AVOIDANCE
- DARK CLOUDS
- REDDENING OF STARLIGHT
- REFLECTION NEBULAE

DETECTED BY :

- ABSORPTION/SCATTERING
OF LIGHT
- IR EMISSION
- CHEMICAL SEPARATION OF
UNPROCESSED METEORITES

EVIDENCE FOR INTERSTELLAR GAS

- EMISSION NEBULAE / H II REGIONS
- INTERSTELLAR ABSORPTION LINES
- 21 CM LINE OF NEUTRAL HYDROGEN
- MOLECULAR MILLIMETER / RADIO LINES

INTERSTELLAR SPACE / GAS + DUST

MOLECULAR CLOUDS

COLD

20-50K

DENSE

$10^3 - 10^5 \text{ cm}^{-3}$

HI CLOUDS

50-150K

$1 - 10^3$

BETWEEN CLOUDS

$10^3 - 10^4 \text{ K}$

0.01

DUST?

CORONAL GAS

$10^5 - 10^6 \text{ K}$

$10^{-4} - 10^{-3}$

DUST?

HII REGIONS

10^4 K

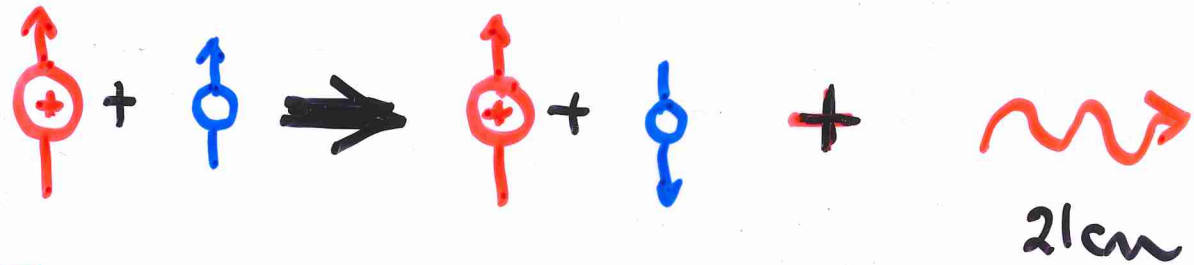
AROUND HOT
STARS

H ATOMS IN GAS CLOUDS

- ATOM-ATOM COLLISIONS LEAD TO SPIN FLIPS



- 21 cm WAVE EMITTED SPONTANEOUSLY



AVERAGE TIME TO EMIT PHOTON
IS A FEW MILLION YEARS

- 21 cm WAVES ALSO ABSORBED

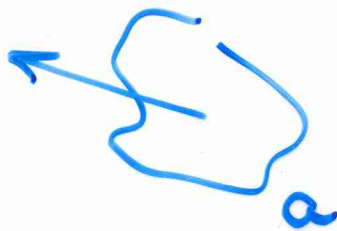
IMPORTANCE

- DUST TRANSPARENT AT 21 cm
∴ CAN DETECT H GAS ACROSS GALAXY
- PRECISE WAVELENGTH
∴ CAN MEASURE RADIAL VELOCITIES

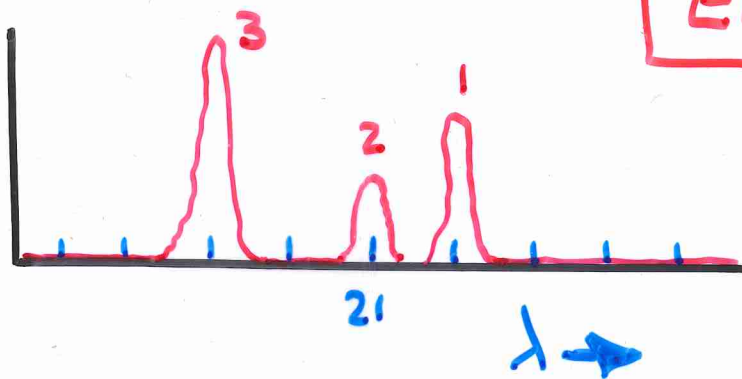
PREDICTED 1944 by H.C. van de HULST

DETECTED 1951 by E. PURCELL + H. EWEN

POWERFUL TOOL FOR RADIO ASTRONOMY



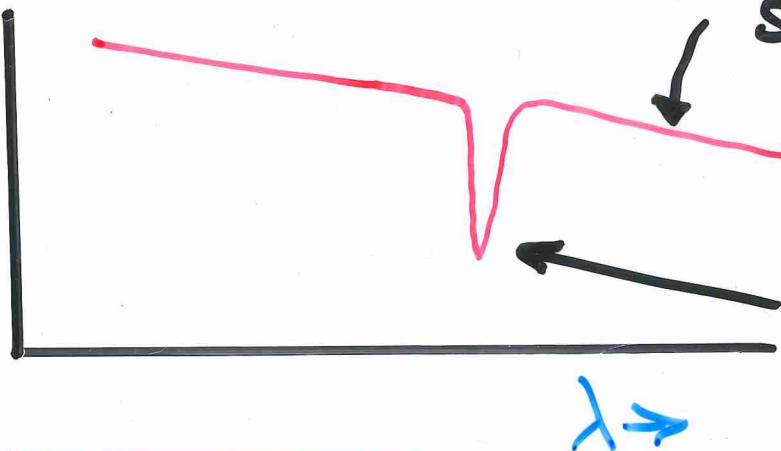
↑
Int.



EMISSION



↑
Int.



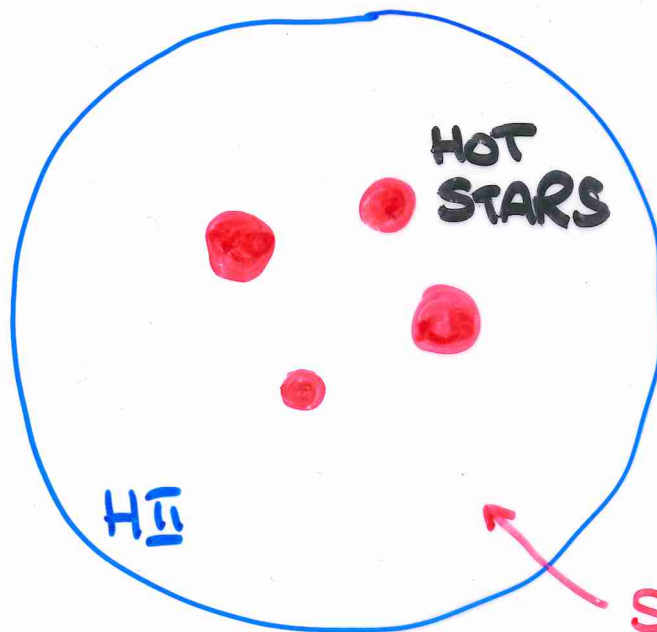
ABSORPTION

CONTINUOUS
SPECTRUM
OF
GALAXY

ABS.
LINE
PRODUCED
BY CLOUD

H II REGIONS

H^+



GAS CLOUD
SURROUNDS
STARS

$H I$

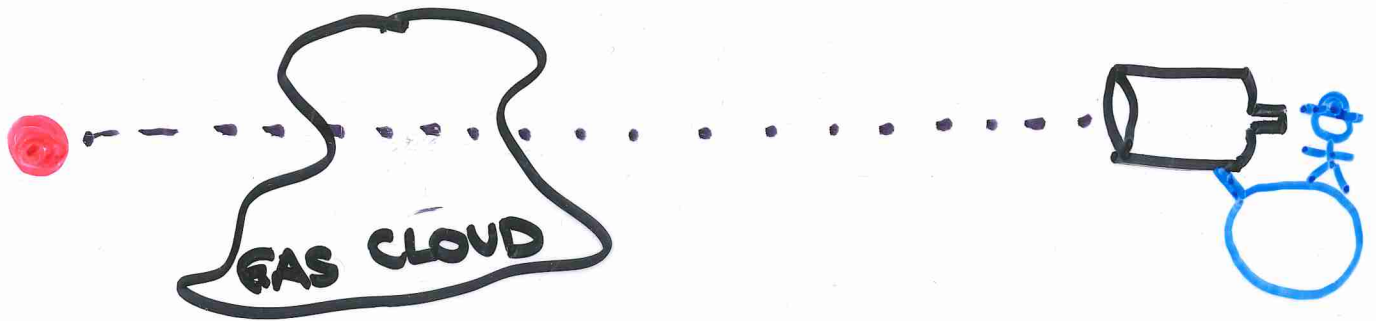
STRÖMGREN
SPHERE

- UV (LYMAN CONTINUUM, $\lambda < 912 \text{ \AA}$)
PHOTONS FROM HOT STARS **IONIZE**
H ATOMS IN GAS
- PROTONS + ELECTRONS RECOMBINE
BUT ARE **QUICKLY REIONIZED**
BALMER (AND OTHER PHOTONS)
EMITTED AS A RESULT OF
RECOMBINATIONS.
- **H II REGION BOUNDARY**
 - **LYMAN PHOTONS ALL CONSUMED**
 - **GAS CLOUD BOUNDARY**

- GAS TEMPERATURE IN $H II$ REGION $\sim 10,000$ K
 - HEATED BY ABSORBING UV OF STARS
 - COOLED BY FORBIDDEN LINES, H EMISSION LINES, ...
-

WHY WILL AN $H II$ REGION SHRINK AS A CLUSTER AGES?

INTERSTELLAR ABSORPTION LINES

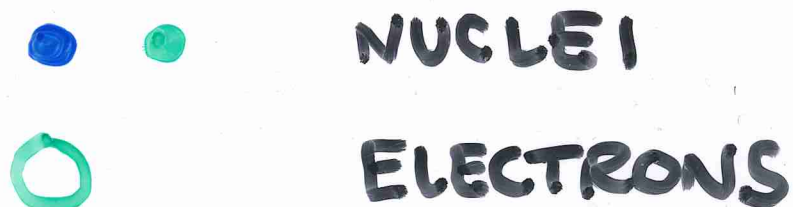
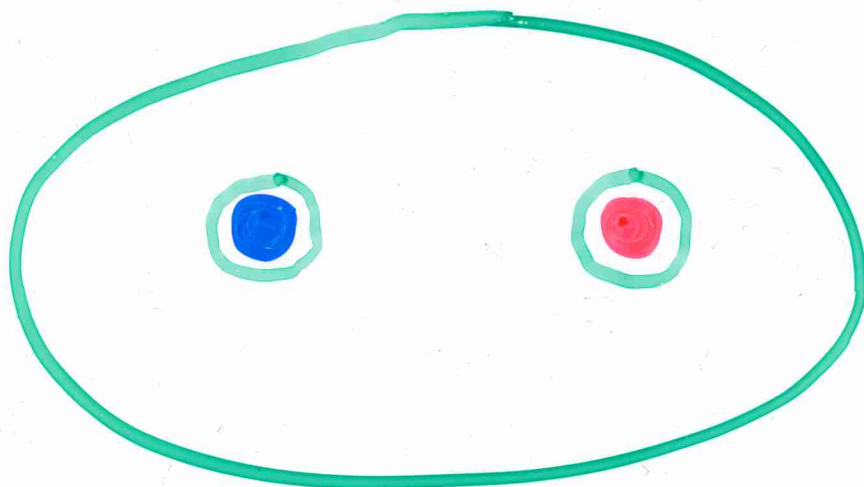


ATOMS, IONS, MOLECULES IN CLOUD
ABSORB PHOTONS AT SPECIFIC
WAVELENGTHS (BOHR ORBIT JUMPS)

→ ABSORPTION LINES IN STELLAR
SPECTRUM

- NEUTRAL SODIUM (Na I)
- NEUTRAL & IONIZED CALCIUM
(Ca I , Ca II)
- RADICALS (CH , CH^+ , CN , CO)

MOLECULES

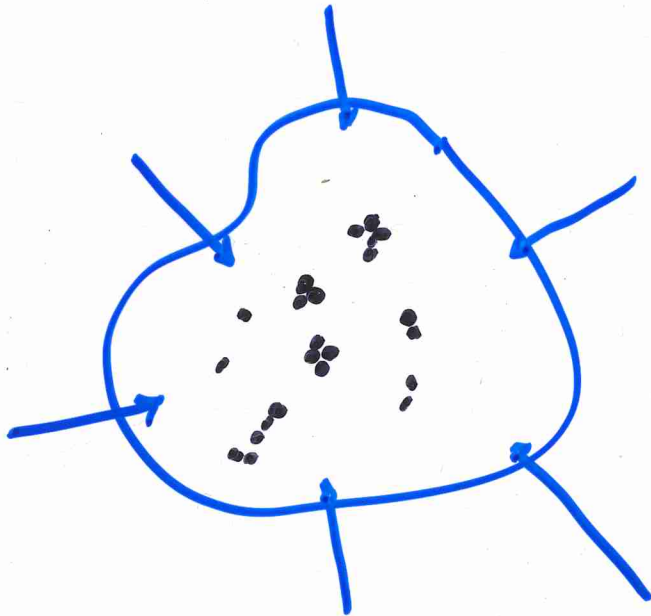


MOLECULE AND ENERGY

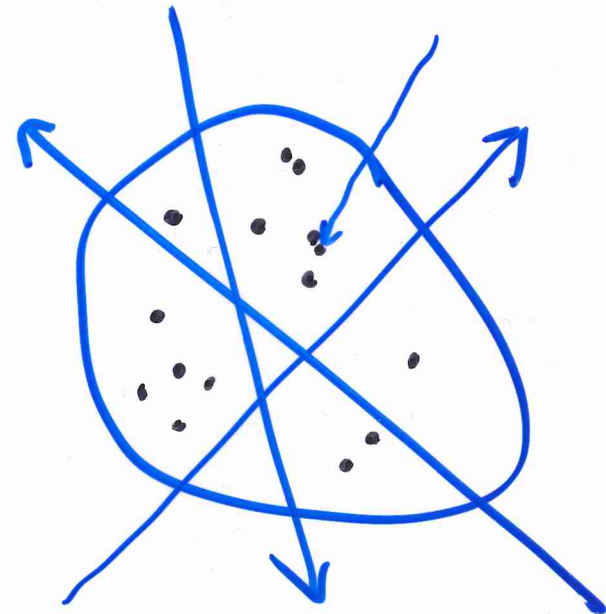
- ELECTRONS - BOHR ORBITS
(UV, VISIBLE)
- NUCLEI - VIBRATE (IR)
- NUCLEI - ROTATE / SPIN
(MM, RADIO)

MOLECULAR/DARK CLOUDS

- DUST SHIELDS GAS FROM UV LIGHT
∴ FRAGILE MOLECULES SURVIVE,
EVEN THRIVE



MOLECULAR
CLOUD



DIFFUSE
CLOUD

INTERSTELLAR MOLECULES

1930s OPTICAL SPECTRA:

absorption lines

CN, CH, CH⁺ in DIFFUSE CLOUDS

1968⁺ MILLIMETER + RADIO
SPECTROSCOPY

NH₃, H₂O, CO, in DARK CLOUDS

1970 ULTRAVIOLET SPECTRA:

absorption lines

H₂, CO in DIFFUSE CLOUDS

CO

CARBON MONOXIDE

 $\text{CH}_3\text{CH}_2\text{OH}$

ETHYL ALCOHOL

 N_2H^+ HCHO

FORMALDEHYDE

 HCOOH

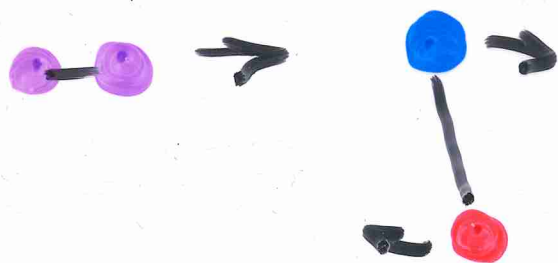
FORMIC ACID

 H_2O

WATER

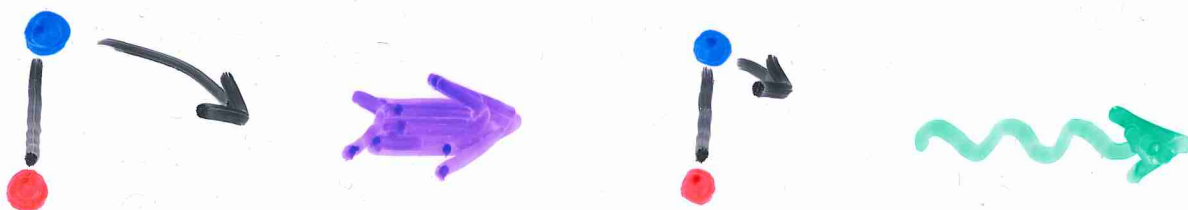
+ ~50 OTHERS SINCE 1970.

1970⁺ → DETECTION OF MOLECULES
BY RADIO/MW EMISSION/
ABSORPTION
LINES



COLLISION → FASTER ROTATION
OF 

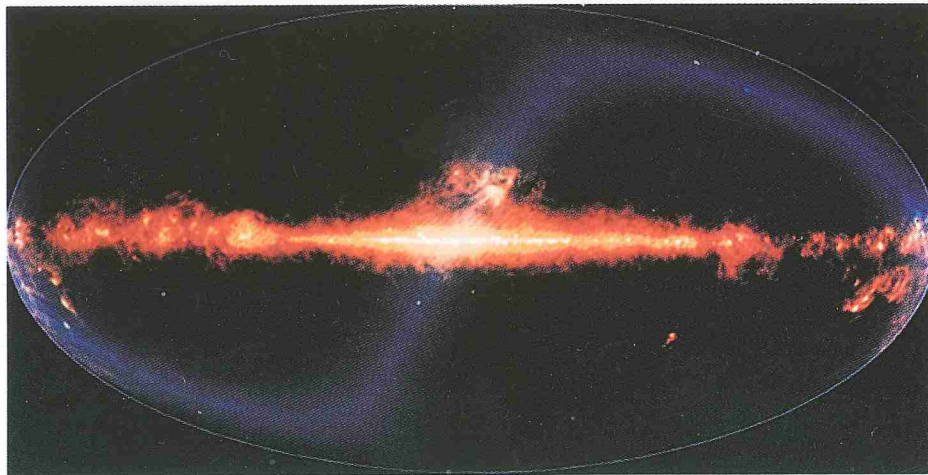
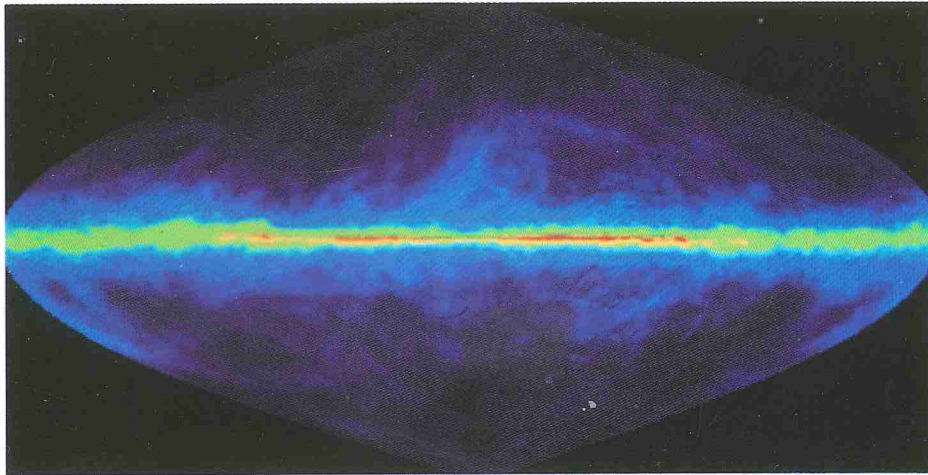
LATER, MOLECULE EMITS PHOTON
TO SLOW DOWN



Extreme Southern Summer Sky

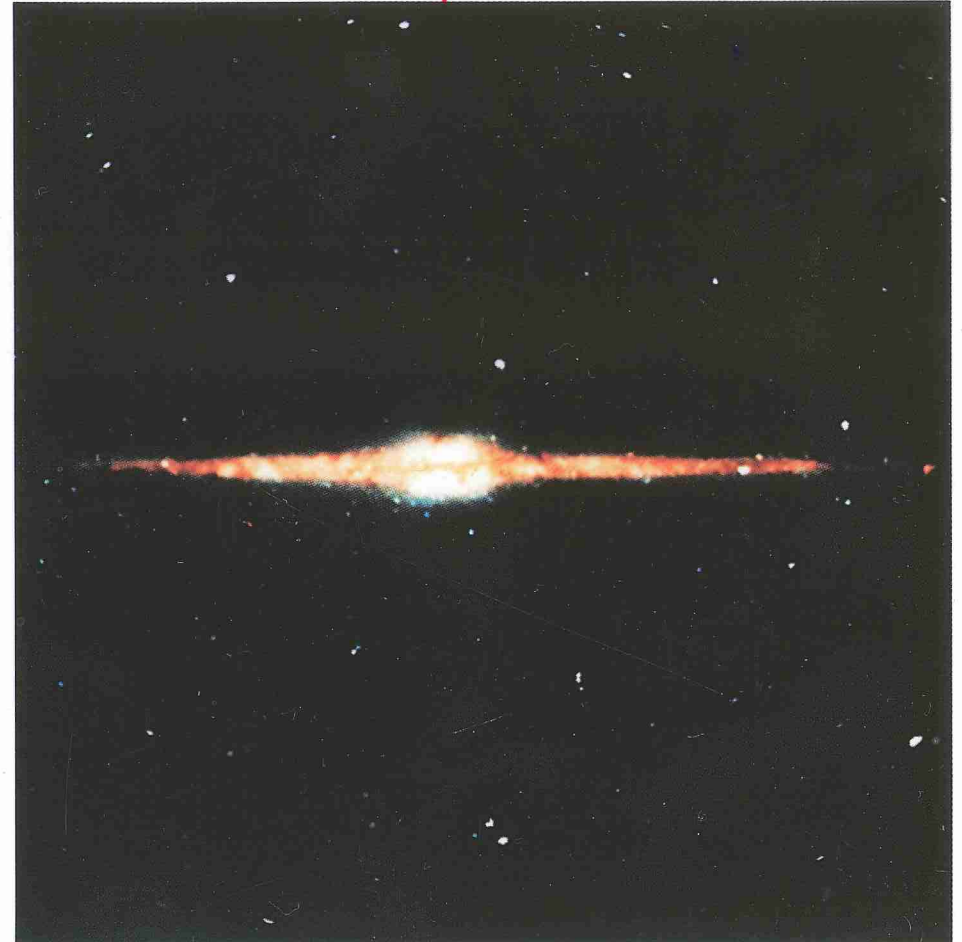


21-cm HI



FAR-IR (DUST)

GALACTIC LONGITUDE
-180° 0° +180°



IR (COOL STARS = RED GIANTS)

ORION

Milky Way seen in cold gas, dust, and cool stars

Hartmann/Impey: The Cosmic Journey, 5th ed., Fig. 23-5

© 1994 Wadsworth, Inc.

MASS OF THE GALAXY?

• COUNT STARS?

BRIGHTNESS $\rightarrow$ LUMINOSITY $\rightarrow$ MASS

PROBLEMS:

- ① LOTS OF MASS IN LOW MASS STARS
OF LOW LUMINOSITY. TOO FAINT
TO SEE BEYOND FEW PARSECS
- ② DUST BEDEVILS THE CENSUS

- MEASURE ORBITAL SPEEDS OF STARS OR GAS CLOUDS ABOUT CENTER OF GALAXY

ANALOGY: PLANETS ORBITING SUN

→ MASS OF SUN

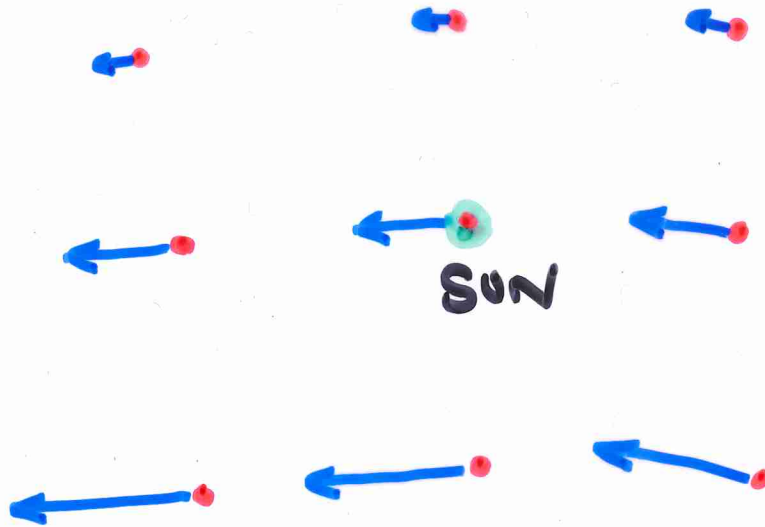


IDEA-#1: LIGHT ($\therefore$ MASS?) OF GALAXIES
LIKE OURS CONCENTRATED IN BULGE

$\therefore$ EXPECT OUTSIDE BULGE, ORBITAL SPEEDS
TO DECREASE WITH INCREASING DISTANCE
FROM BULGE

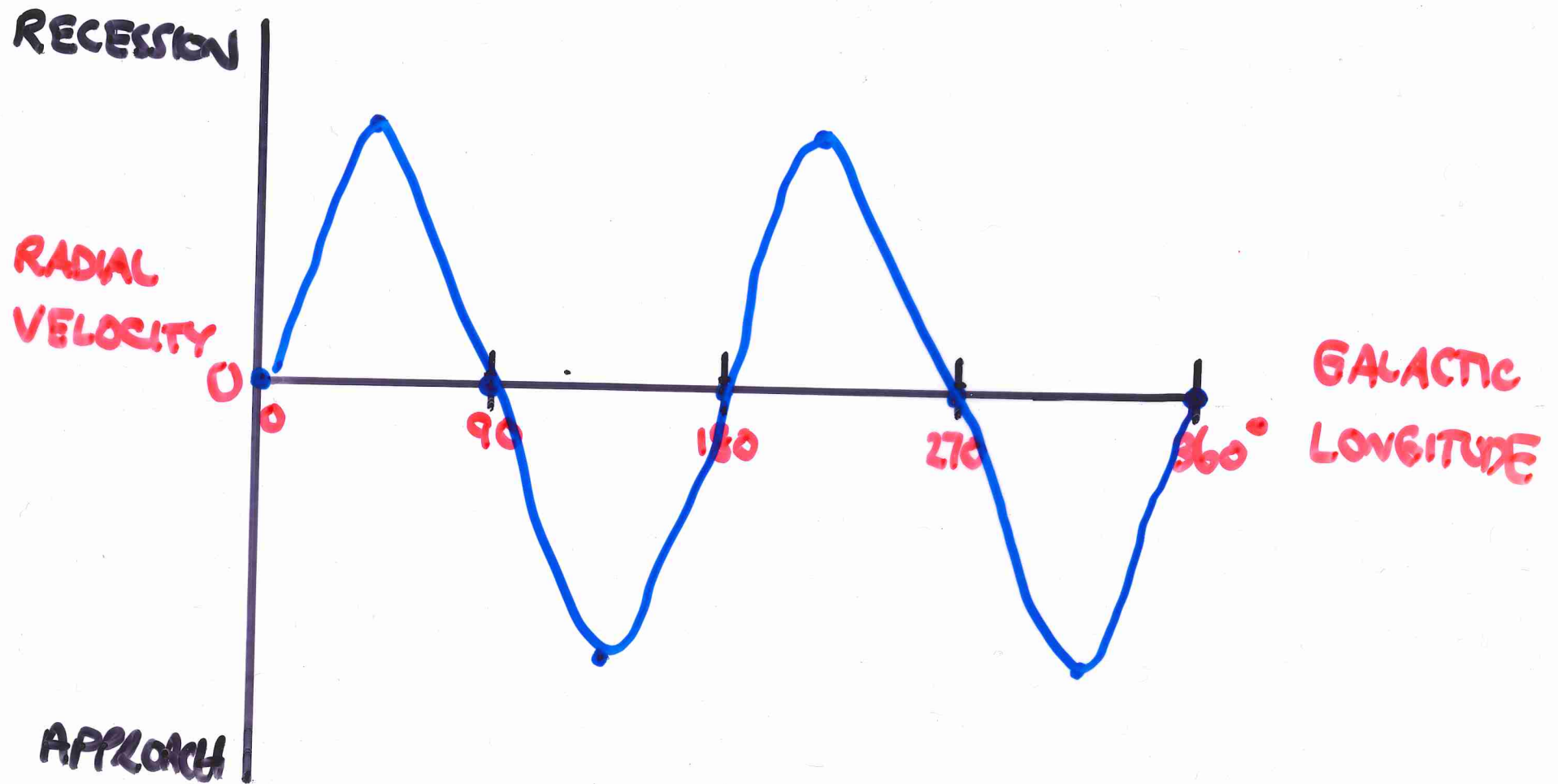
KEPLERIAN MOTION: $V \propto \frac{1}{\sqrt{R}}$ (PLANETS)

STARS & ROTATION OF GALAXY



⇓
TO CENTER
OF
GALAXY

- MEASURE RADIAL VELOCITIES
FOR STARS AT ALL GALACTIC
LONGITUDES
- MEASURE 'PROPER MOTIONS' FOR....



- GALACTIC ROTATION (via STARS) discovered by OORT and LINDBLAD in 1920s

• PROBLEMS

- CANNOT OBSERVE STARS FAR FROM
SUN DUST!

- ACCURATE DISTANCES UNOBTAINABLE
FOR DISTANT STARS DUST!

Now
HERE

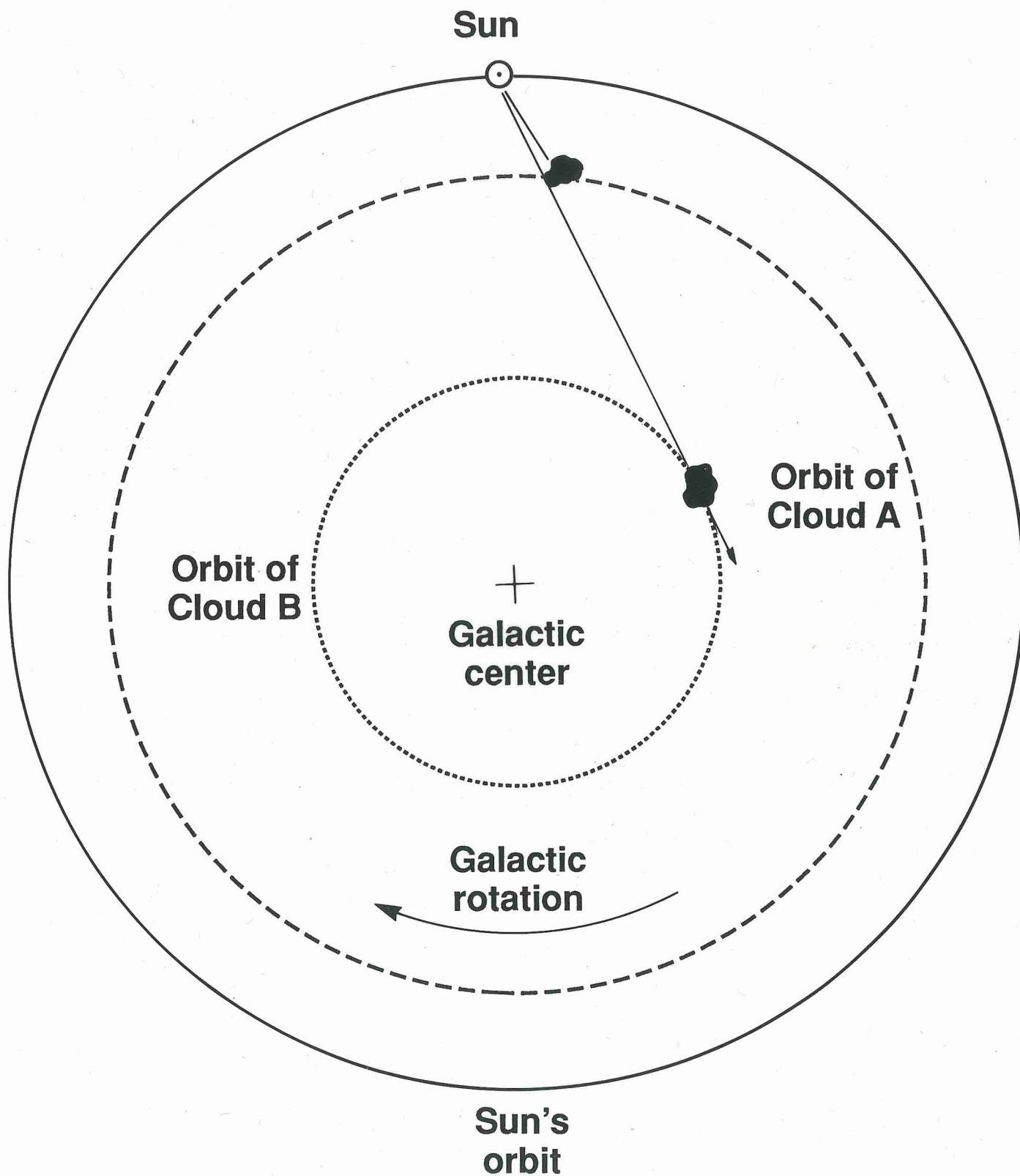
• RESULTS

- SUN AND NEARBY STARS ORBIT AT
~ 220 km/s, TAKE ~240 million years

- IMPLIES $M_{\text{GAL}} \sim 10^{11} M_{\odot}$

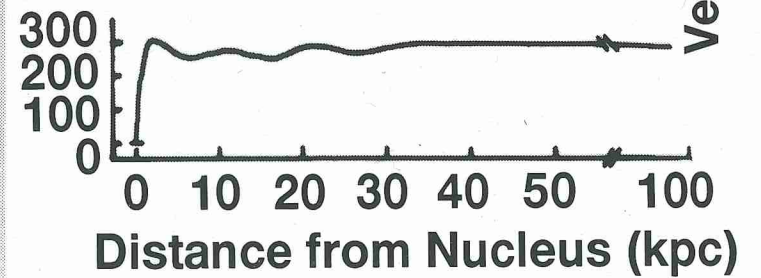
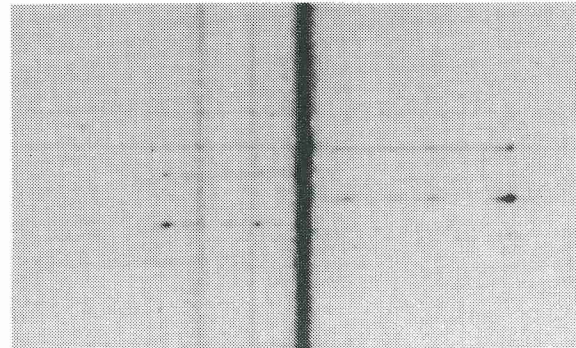
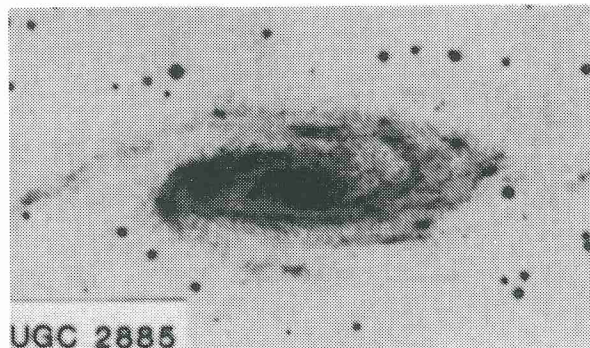
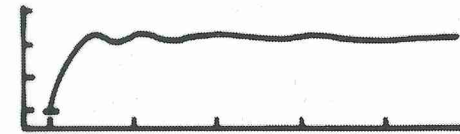
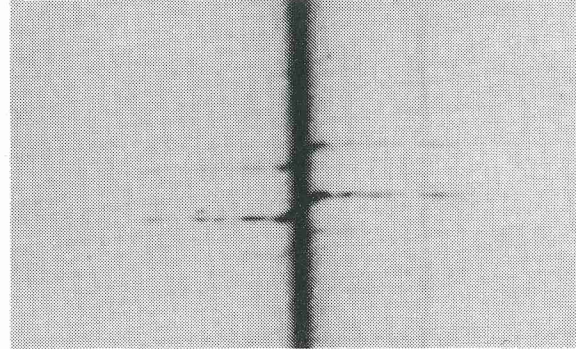
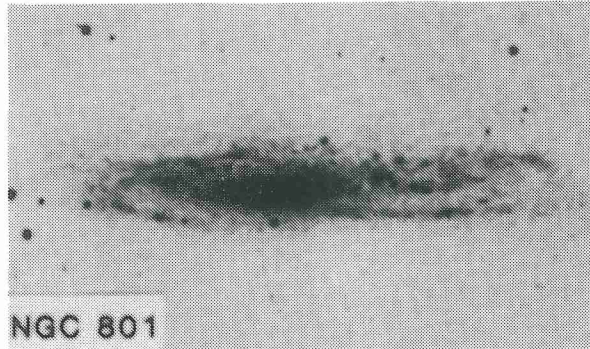
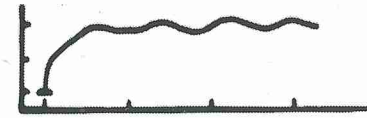
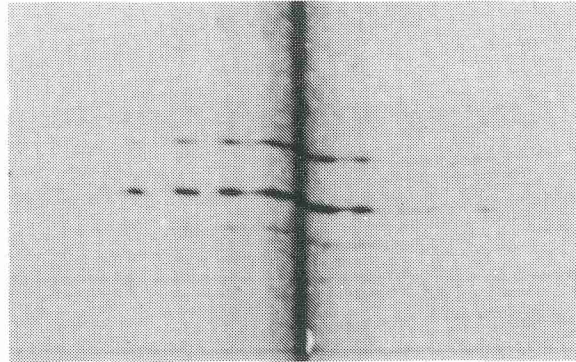
- BUT CANNOT CONFIRM $V \propto \frac{1}{\sqrt{R}}$ (KEPLERIAN)

- ENTER RADIO ASTRONOMY AND THE HI 21 cm LINE
- OBSERVE HYDROGEN CLOUDS FROM ANYWHERE IN GALAXY
- RADIAL VELOCITY VS DISTANCE FROM GALACTIC CENTER OBTAINED FROM 0 to 15,000 pc.



Using the Doppler shift to plot a cloud's position

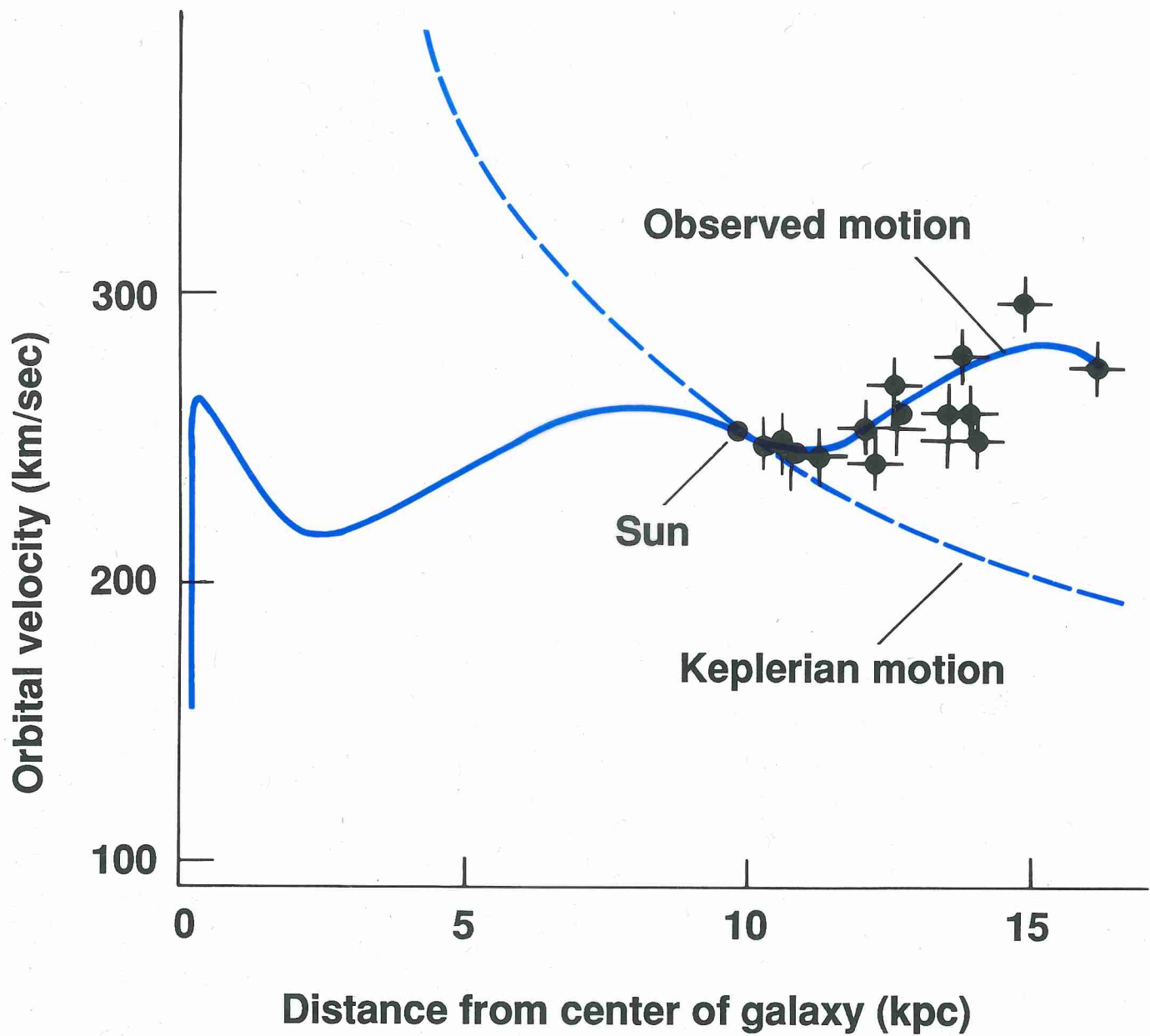
OTHER SPIRAL GALAXIES



Velocity in Plane of Galaxy (km/s)

Rotation curves for spiral galaxies

Hartmann/Impey: The Cosmic Journey, 5th ed., Fig. 24-24

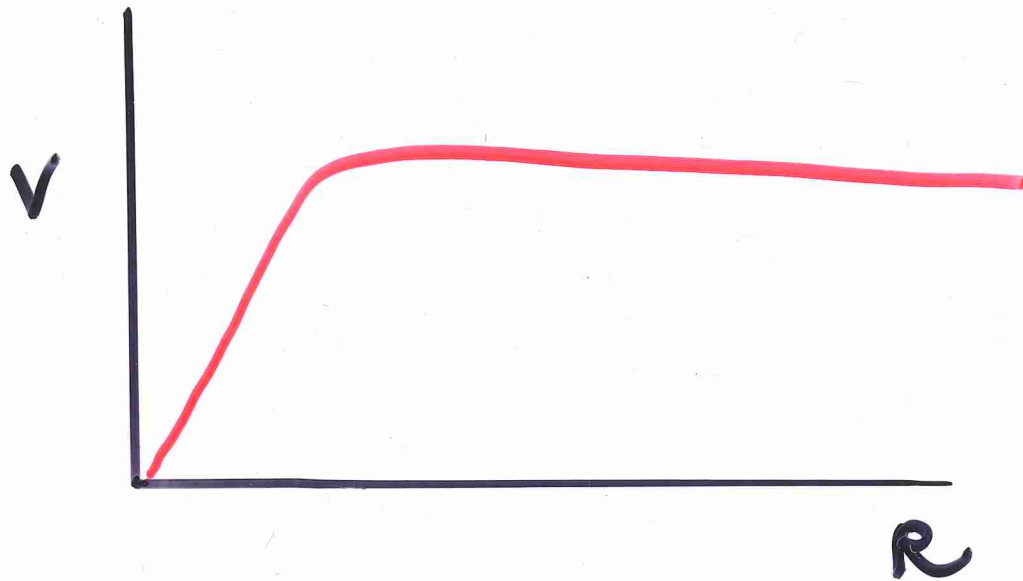


SEEDS, FIG. 15-10

Orbital velocity of stars in the galaxy

Seeds: Horizons, 1995 ed., Fig. 12-11; Foundations of Astronomy, 1994 ed., Fig. 15-13

FLAT ROTATION CURVES



- VELOCITY INCREASES OUT THRU' BULGE
- FLAT CURVE IMPLIES MASS AT LARGE DISTANCES FROM BULGE

$$\rightarrow m_{\text{GAL}} \sim 10^{12} m_{\odot}$$

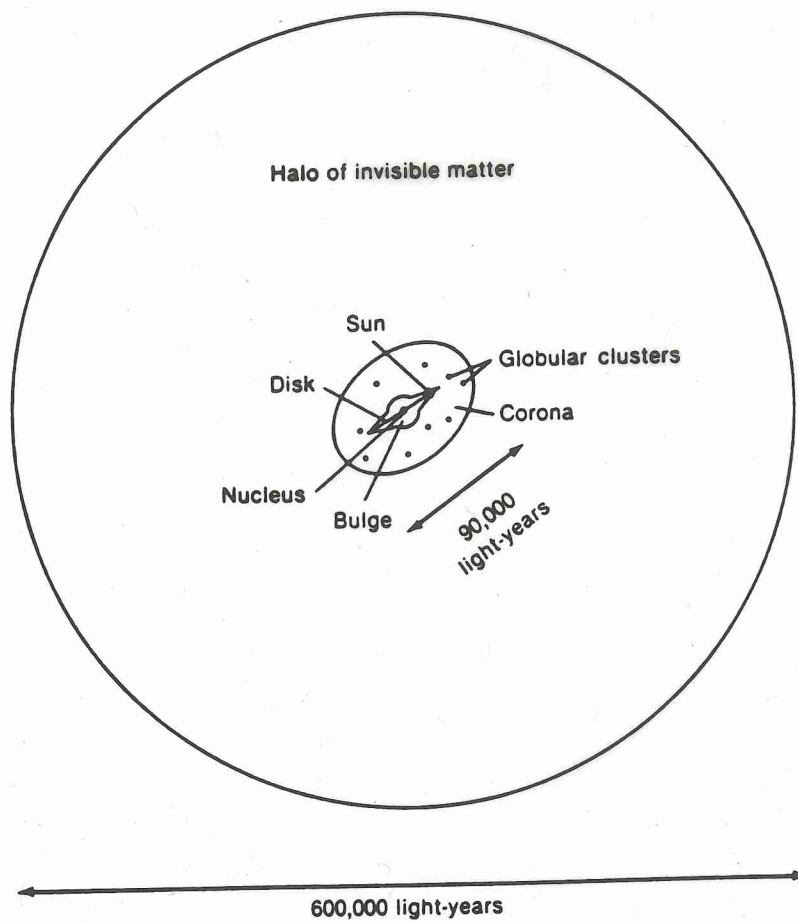


Fig. 53. *Something dark around galaxies.* Studies of the motions of stars and gas in spiral galaxies show that the latter are surrounded by enormous invisible halos, five to ten times as large and massive as the visible part. This invisible matter appears to be present everywhere in the universe, but its true nature remains a mystery.

DARK MATTER / 'MISSING' MASS

- MASS REVEALED BY ITS GRAVITATIONAL FORCE BUT NOT (YET?) DETECTED BY ELECTROMAGNETIC RADIATION
- 90-99% of MASS IN UNIVERSE IS DARK

#2 PROBLEM IN
CONTEMPORARY ASTRONOMY

#1 = DARK ENERGY

WHAT IS DARK MATTER?

- HERETICAL VIEWS

[NEPTUNE, MERCURY]

UNDERSTANDING OF GRAVITATION AT FAULT

e.g. $F = G \frac{m_1 m_2}{d^?}$ NOT $F = G \frac{m_1 m_2}{d^2}$

- ORDINARY MATTER

NEED LOW LUMINOSITY OBJECTS

BROWN DWARFS, PLANETS, ROCKS

DEAD STARS (WD, NS, BH)

MASSIVE BLACK HOLES

NO! — see
COSMIC
MICROWAVE
BACKGROUND

- NEUTRINOS

MAY HAVE A LITTLE MASS, LOTS OF THEM,
INCLUDING BIG SUPPLY FROM BIG BANG

WAS #1 PROBLEM IN PHYSICS OF ELEMENTARY
PARTICLES

COUPLES PHYSICS TO ASTRONOMY!

- EXOTIC PARTICLES

- SHADOW MATTER (normal matter but experiencing only gravitational force)

- PHOTINOS, GRAVITINOS, GHOSTINOS!

- LABORATORY EXPTS UNDERWAY TO
DETECT WIMPS

STELLAR POPULATIONS

INTRODUCED BY

WALTER BAADE

LOCATIONS

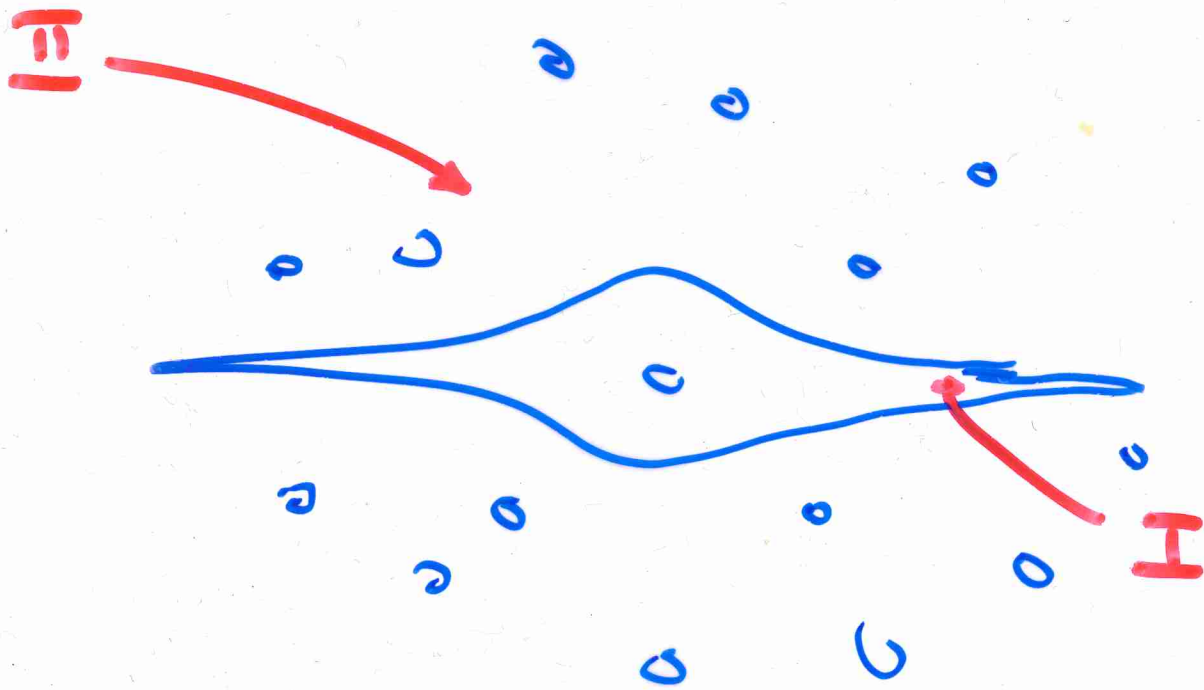
MOTIONS

CHEMICAL COMPOSITIONS

AGE

POP. I & II

LOCATION IN GALAXY



I IN DISK WITH GAS/DUST

II IN HALO

CHEMICAL COMPOSITIONS

I 'METAL' CONTENT $\sim$ SOLAR.

FROM $2 \times$ SOLAR TO $1/10$ SOLAR

II 'METAL' CONTENT $\ll$ SOLAR,

FROM $1/10$ TO $1/10000$ TO ? OF
SOLAR.

AGE

I

YOUNG TO MIDDLE AGED :

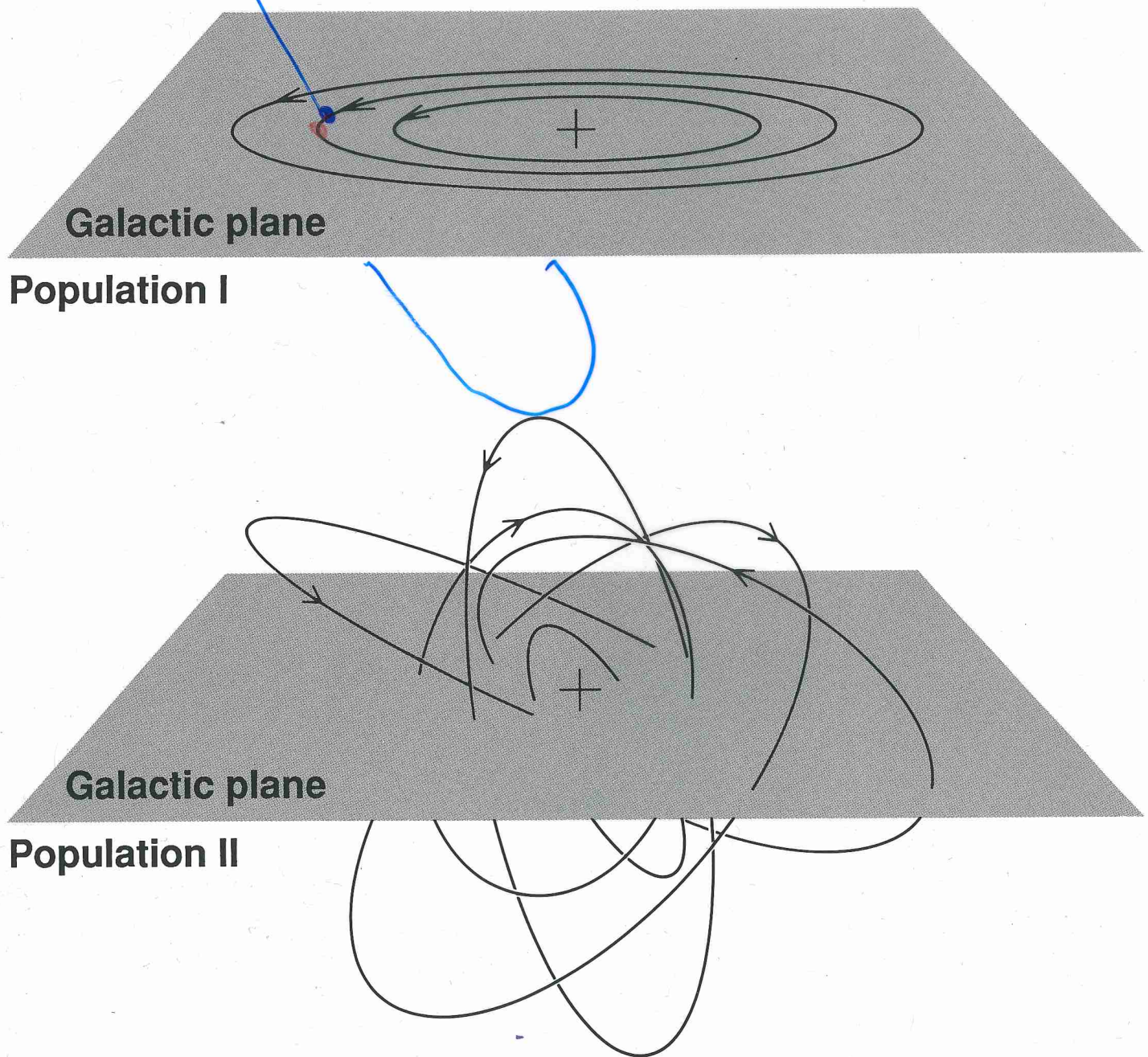
0 YRS TO 10 BILLION YRS

II

OLD - 15 BILLION YRS WITH

A SPREAD OF A FEW BILLION
YRS.

MOTIONS



POP II = HIGH VELOCITY STARS

Comparison of orbits of disk Population I and halo Population II stars

Pop. I or II ?

O STAR

GLOBULAR CLUSTER

H I CLOUD

H II REGION

SOLAR COMPOSITION F STAR

TYPE II SN

TYPE I SN

METAL-POOR

M DWARF

METAL-RICH

M DWARF