Discovery and Early Characterization of Interstellar Dust

B. T. Draine

Princeton University and *Osservatorio Arcetri*

Bruno Rossi (1905-1993)

Bruno Rossi

- Founded Univ. of Firenze physics institute at Arcetri (1920)
- Cosmic ray studies beginning in 1929
- Univ. of Padua (1932-38) ... ,
  University of Chicago (1939)
  Cornell Univ. (1942)
  Los Alamos (1943-46)
  MIT (1946-70)
  Univ. of Palermo (1974-80)
- Worked with Riccardo Giacconi to initiate X-ray astronomy from sounding rockets (and ultimately satellites). Discovery of extra-solar X-rays (Giacconi et al. 1962)
- Connection to interstellar dust?
  X-ray imaging and spectroscopy now provide valuable constraints on grain size distribution and composition.

Plan

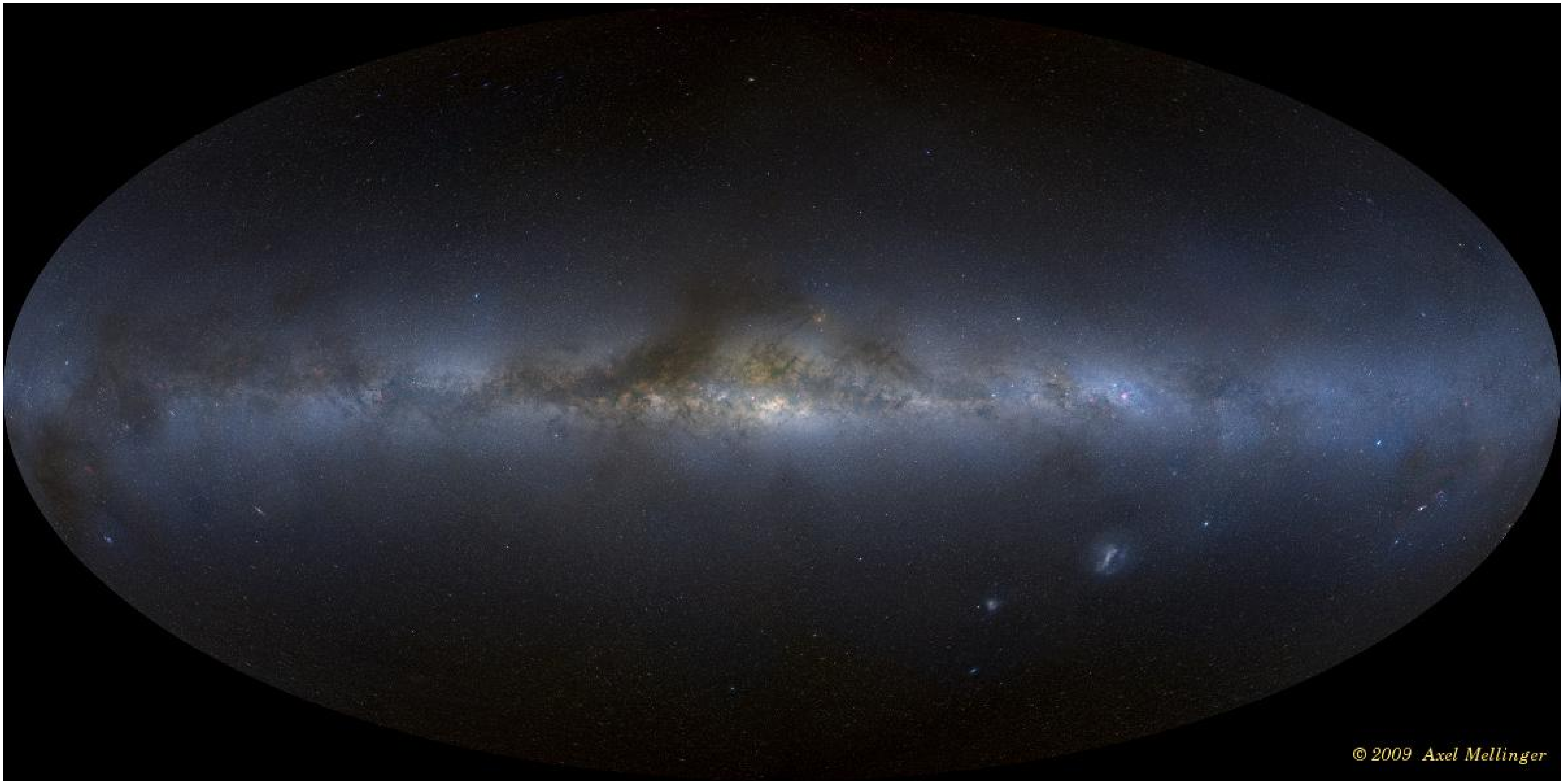
Today: *Discovery and Early Characterization of Interstellar Dust*

1. **Some Examples of Obscuration**
2. **First Recognition of Obscuring Dust**
3. **Early Characterization of Reddening and Extinction**
4. **First Theoretical Discussion of Particle Size**
5. **Early Modeling of the Size Distribution (1940s and 50s)**
6. **Discovery of Polarization of Starlight by the Interstellar Medium**
7. **UV and IR Spectroscopy of Dust**
8. **Recognition of Stars as Producers of Dust**

Friday: *Modern Observations of Interstellar Dust*

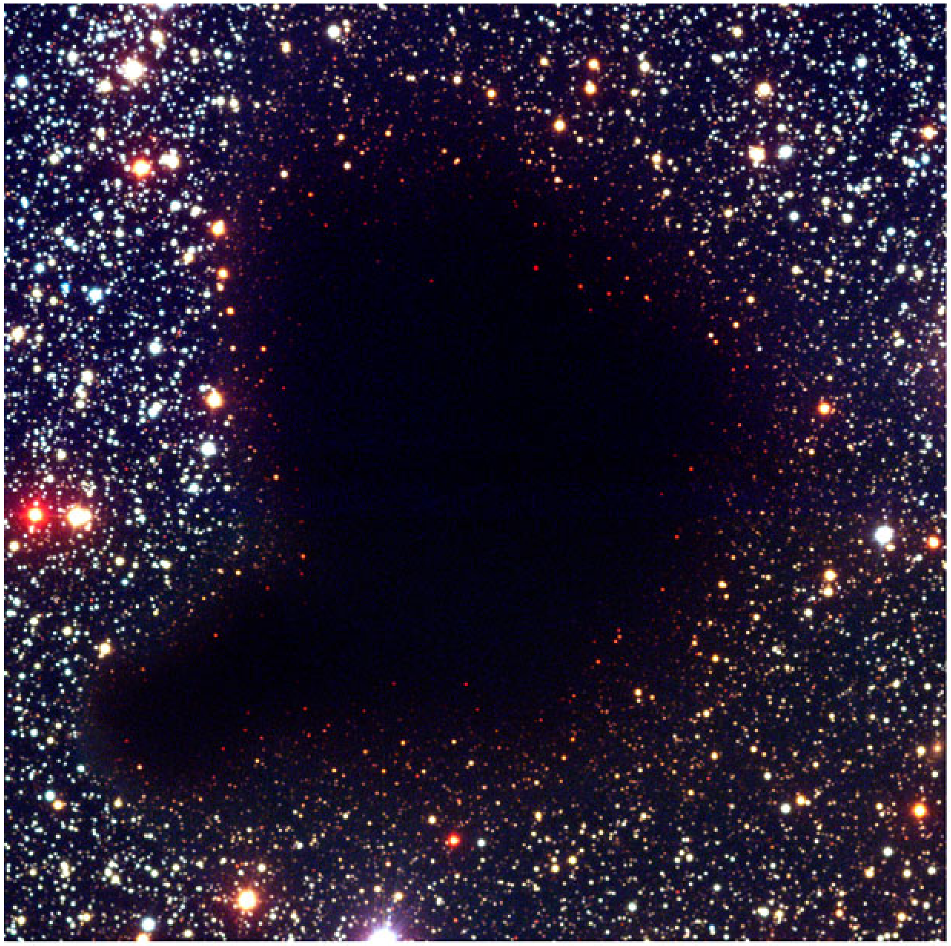
Monday: *Theoretical Models for Interstellar Dust*

Obscuration: Some Examples

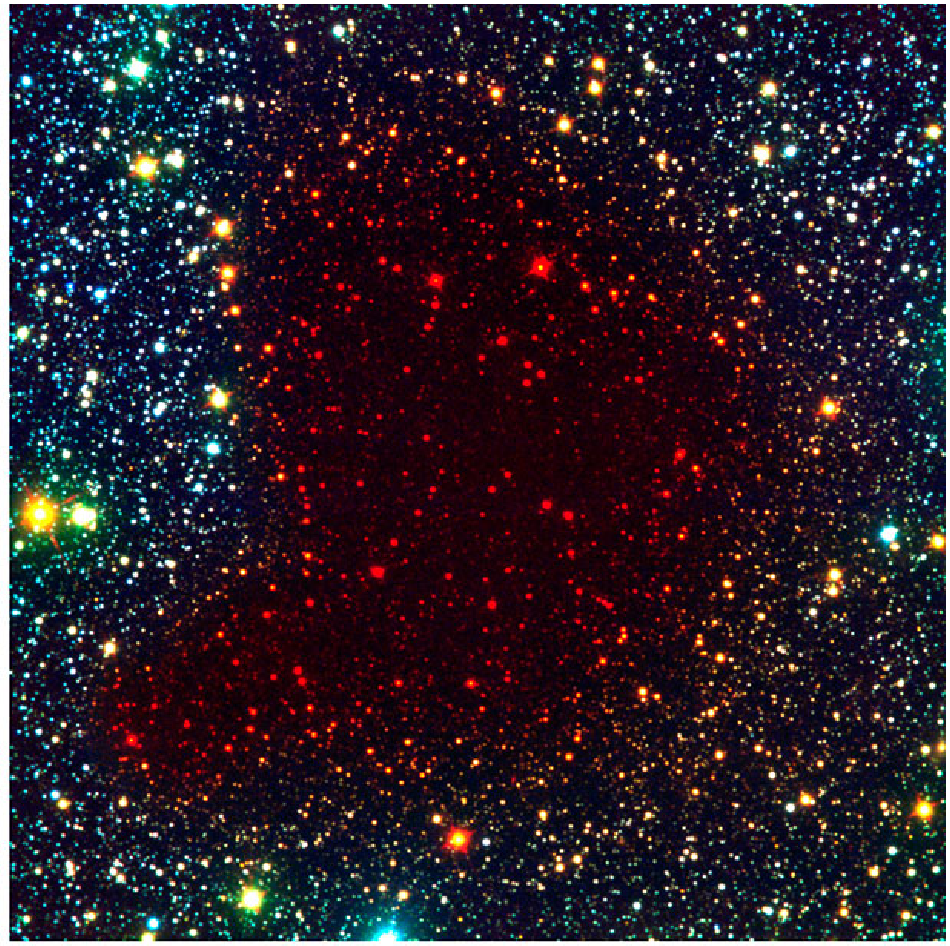


Full-sky view of Milky Way in visible light (Mellinger 2009)

Obscuration: Some Examples



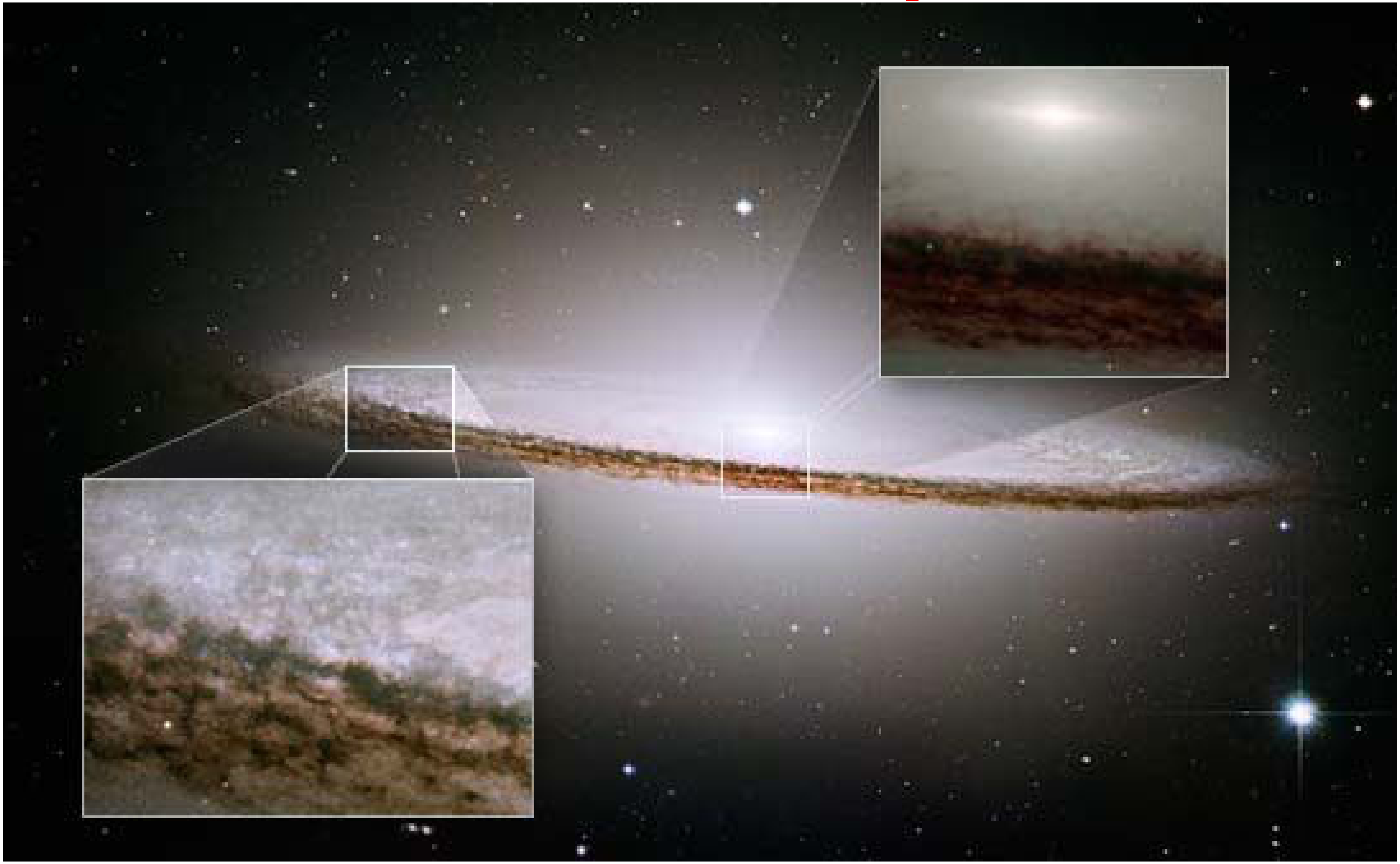
B, V, I



B, I, K

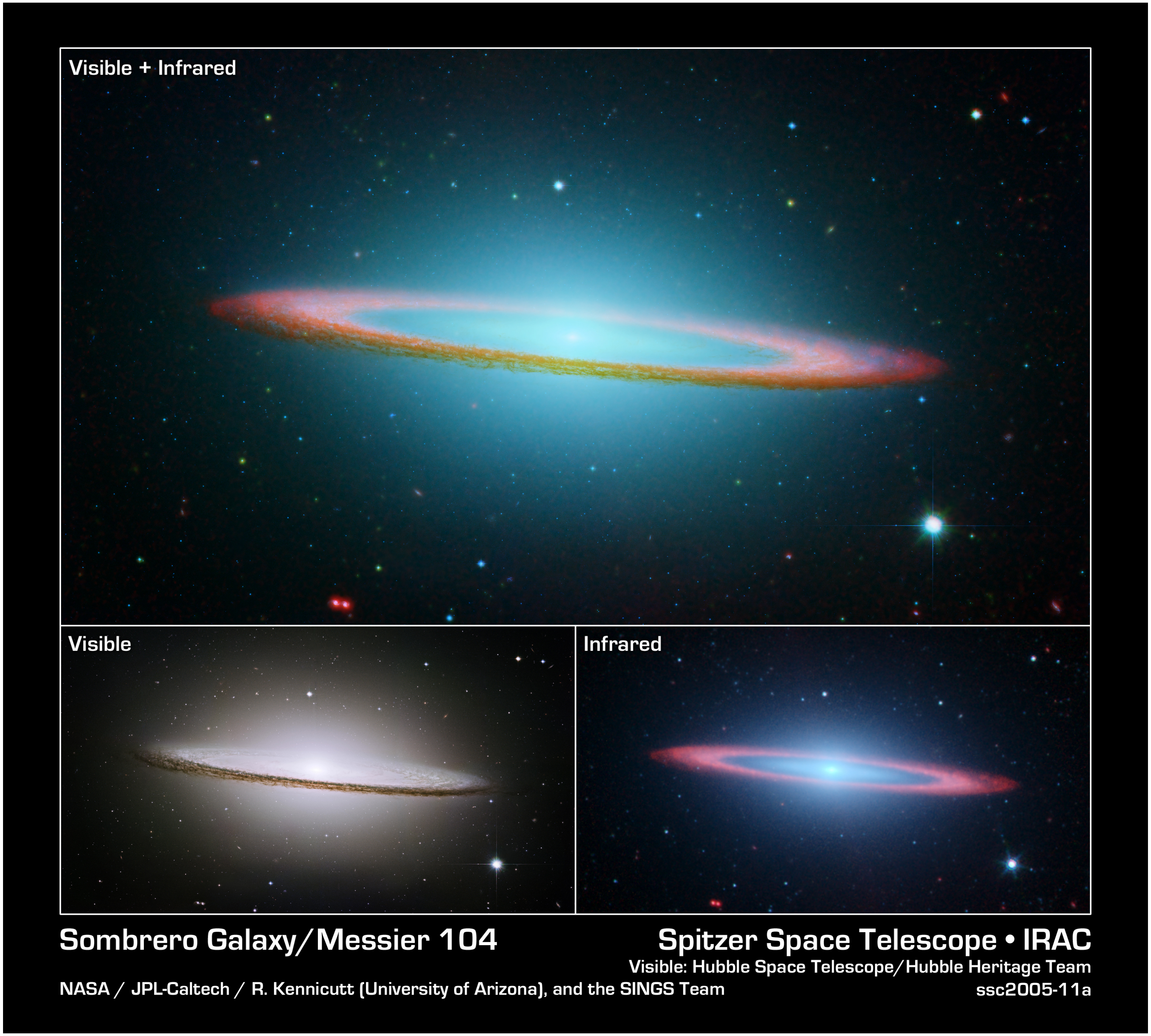
Dark Cloud Barnard 68 ($M \approx 2M_\odot$, $D \approx 0.1\,\mathrm{pc}$).
Image courtesy of J. Alves, C.J. Lada, and E. Lada

Obscuration: Some Examples

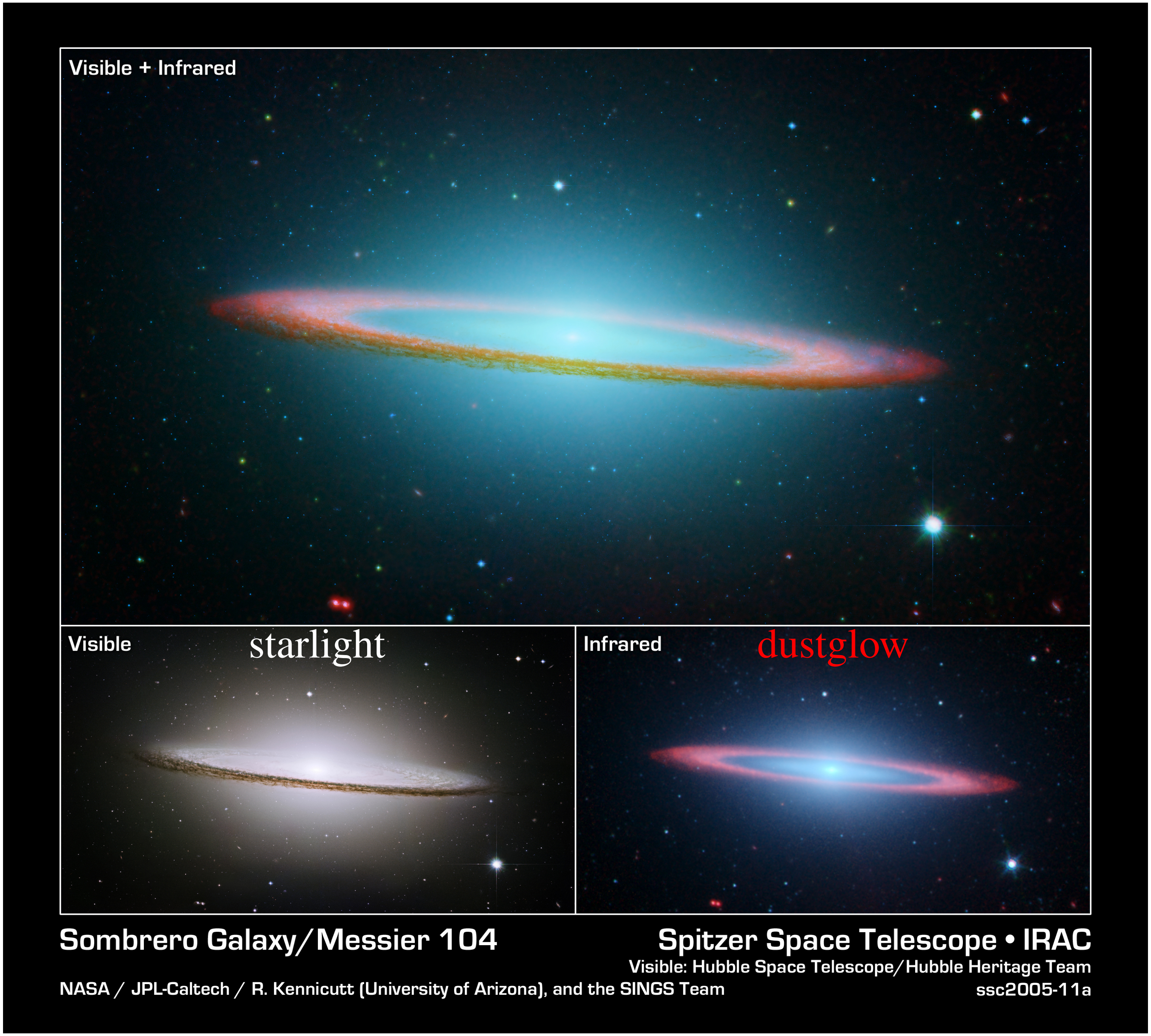


Detailed views of the Sombrero Galaxy (Hubble Space Telescope)

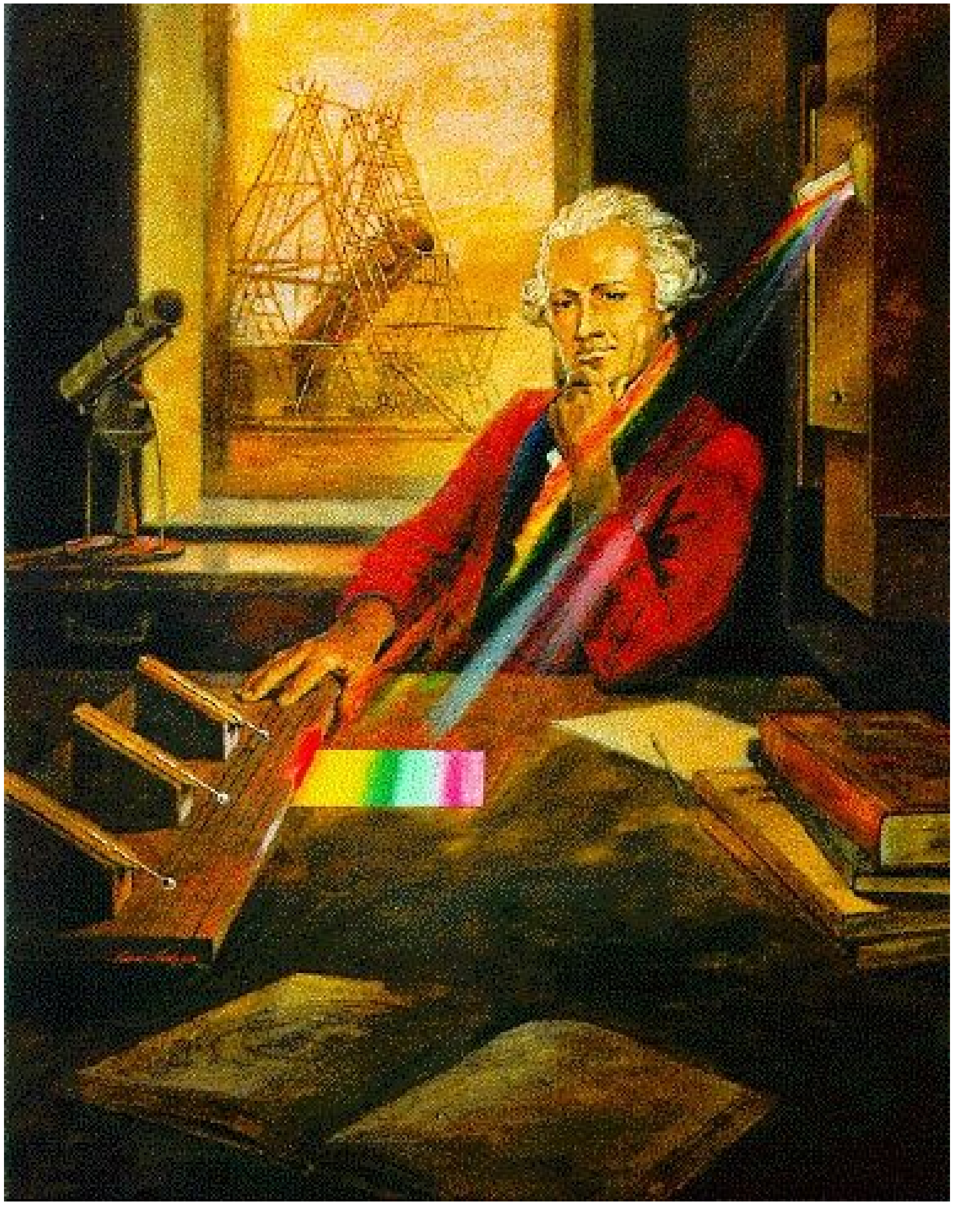
Obscuration and Infrared Emission



Obscuration and Infrared Emission



When Was Obscuration First Noticed?



William Herschel, 1738-1822

- Project: star counts
  carried out "sweeps", counting stars visually
- Noticed that star densities showed large variations in some areas.
- **Why?**

When Was Obscuration First Recognized?

Herschel (1785), "On the Construction of the Heavens",
Philosophical Transactions Series I, **75**, 213-266

XII. *On the Conſtruction of the Heavens.*
By William Herſchel, *Eſq. F. R. S.*

Read February 3, 1785.

THE ſubject of the Conſtruction of the Heavens, on which I have ſo lately ventured to deliver my thoughts to this Society, is of ſo extenſive and important a nature, that we cannot exert too much attention in our endeavours to throw all poſſible light upon it; I ſhall, therefore, now attempt to purſue the delineations of which a faint outline was begun in my former paper.

When Was Obscuration First Recognized?

Herschel (1785), 38 pages later...

An Opening in the heavens.

Some parts of our ſyſtem indeed ſeem already to have ſuſtained greater ravages of time than others, if this way of expreſſing myſelf may be allowed; for inſtance, in the body of the Scorpion is an opening, or hole, which is probably owing to this cauſe. I found it while I was gaging in the parallel from 112 to 114 degrees of north polar diſtance. As I approached the milky way, the gages had been gradually running up from 9,7 to 17,1; when, all of a ſudden, they fell down to nothing, a very few pretty large ſtars excepted, which made them ſhew 0,5, 0,7, 1,1, 1,4, 1,8; after which they again roſe to 4,7, 13,5, 20,3, and ſoon after to 41,1. This opening is at leaſt 4 degrees broad, but its height I have not yet aſcertained. It

A Hole in the Sky?

William Herschel: "In the body of the Scorpion is an opening, or hole..."

$\sim 30 \times 20$ arcmin region centered on RA=16h 23m 25s, DEC=-24 deg.
(from Google Sky)

William Herschel: Observing and Theorizing...

(M80)

It is remarkable, that the 80 *Nebuleuſe ſans étoiles* of the *Connoiſſance des Temps*, which is one of the richeſt and moſt compreſſed cluſters of ſmall ſtars I remember to have ſeen, is ſituated juſt on the weſtern border of it, and would almoſt authoriſe a ſuſpicion that the ſtars, of which it is compoſed, were collected from that place, and had left the vacancy. What adds

Idea: Stars now composing M80 (about 2 deg S of the "hole") were drawn from the field, leaving a deficiency nearby.

Obscuration Not Recognized As Such

Herschel (1785) Map of the Galaxy
Based on Star Counts

When was Obscuration First Recognized as Obscuration?

Edward Pickering (1897), discussing **star counts**:

Professor Bailey has recently made a count of the stars in the vicinity of several clusters. An enlargement was made of a photograph of the Pleiades taken with the Bruce telescope and having an exposure of six hours. A region 2° square, with η Tauri (Alcyone) in the center was divided into 144 smaller squares, each 10′ on a side. The stars in each of these squares were then counted. The total number thus found was 3972, an average of 28 in each square. The 42 squares including the brighter stars in the group contain 1012 stars, an average of 24 per square. It therefore appears that the total number of stars in the region of the Pleiades is actually less than that in adjacent portions of the sky, of equal area, and it is much less than the corresponding number in many parts of the Milky Way. The Pleiades must, therefore, be regarded, first as a group consisting of comparatively bright stars; secondly, if we omit the bright stars, the number of faint stars will be much less than in the adjacent portions of the sky. This absorption of the faint stars is probably due to the nebulosity surrounding this group. A similar absence of faint stars is noticeable near other diffused nebulae, for example, that surrounding *N. G. C.* 6726–7. This condition would be explained if we assume that stars have not yet been formed by the condensation of this portion of the nebula or that the latter is less distant and slightly opaque.

Edward Charles Pickering (1846-1919)

Quantitative Studies of Reddening

J. C. Kapteyn (1909a):

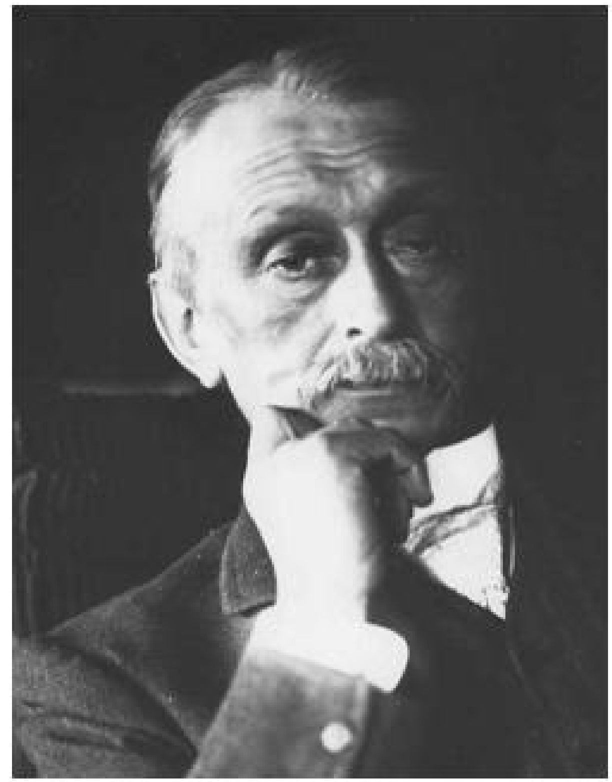
ON THE ABSORPTION OF LIGHT IN SPACE[1]

BY J. C. KAPTEYN[2]

Undoubtedly one of the greatest difficulties, if not the greatest of all, in the way of obtaining an understanding of the real distribution of the stars in space, lies in our uncertainty about the amount of loss suffered by the light of the stars on its way to the observer. For the sake of brevity and in accordance with what has been done by other astronomers, I will designate this loss by the name of *absorption* of light, though the loss caused by *scattering* of light will be included.

Elsewhere (*Astronomical Journal*, No. 566, **24**, 115, 1904) I tried to show how fundamentally our results for the arrangement of the stars in space are changed by admitting even an absorption of light considered as small by some astronomers.

Now there can be little doubt, in my opinion, about the existence of absorption in space and I think that even a good guess as to the order of its amount can be made. For, first, we know that space contains an enormous mass of meteoric matter. This matter must necessarily intercept some part of the star-light.



Jacobus Cornelius Kapteyn 1851-1922

Quantitative Studies of Reddening

Kapteyn (1909a):

Meanwhile it cannot be denied that the truly fundamental importance of the absorption of light makes it highly desirable to find still other methods, depending on quite different data. Such a new method could probably be obtained if it turns out that the absorption in interstellar space is more or less *selective*. If the absorption and scattering of light by meteoric matter is really sensible, then there can be no reasonable doubt but that the violet end of the spectrum must be more strongly affected than the less refrangible rays.

Kapteyn (1909b):

ON THE ABSORPTION OF LIGHT IN SPACE[1]

SECOND PAPER

BY J. C. KAPTEYN[2]

1. *Data on which the investigation is based.*—After deriving the results of my first paper,[3] which make it probable that there is an appreciable amount of selective absorption of light in space, I was naturally anxious to obtain some quantitative determination of this loss. In the present paper I have tried to carry through such a determination.

The phenomenon must manifest itself in this, that, *ceteris paribus*, the more distant stars will be redder than the nearer ones. As a

Quantitative Studies of Reddening: Trumpler (1930)

ABSORPTION OF LIGHT IN THE GALACTIC SYSTEM

BY ROBERT J. TRUMPLER

For more than a century astronomers have interested themselves in the question: Is interstellar space perfectly transparent, or does light suffer an appreciable modification or loss of intensity when passing through the enormous spaces which separate us from the more remote celestial objects? Any effect of this kind is generally referred to as "absorption of light in space," whatever the peculiar physical process assumed for its cause. Various hypotheses have been proposed for the latter. The older views attributed such absorbing properties to the hypothetical ether itself; but at present we think rather of a much rarefied invisible material medium and admit that the latter is not necessarily of uniform distribution throughout all space. According to prevailing physical theories, light passing through such a material medium will be affected in various ways: Aside from possible refraction and dispersion effects, light may be absorbed by free atoms or molecules; it may be scattered by free electrons, atoms, or molecules, or by solid particles of extremely small size; and finally light may be obstructed by larger bodies, such as meteorites. The space absorption of light is thus intimately related to the question of the presence, distribution, and constitution of dark matter in the universe.

Robert J. Trumpler
(1886-1956)

Trumpler (1930)

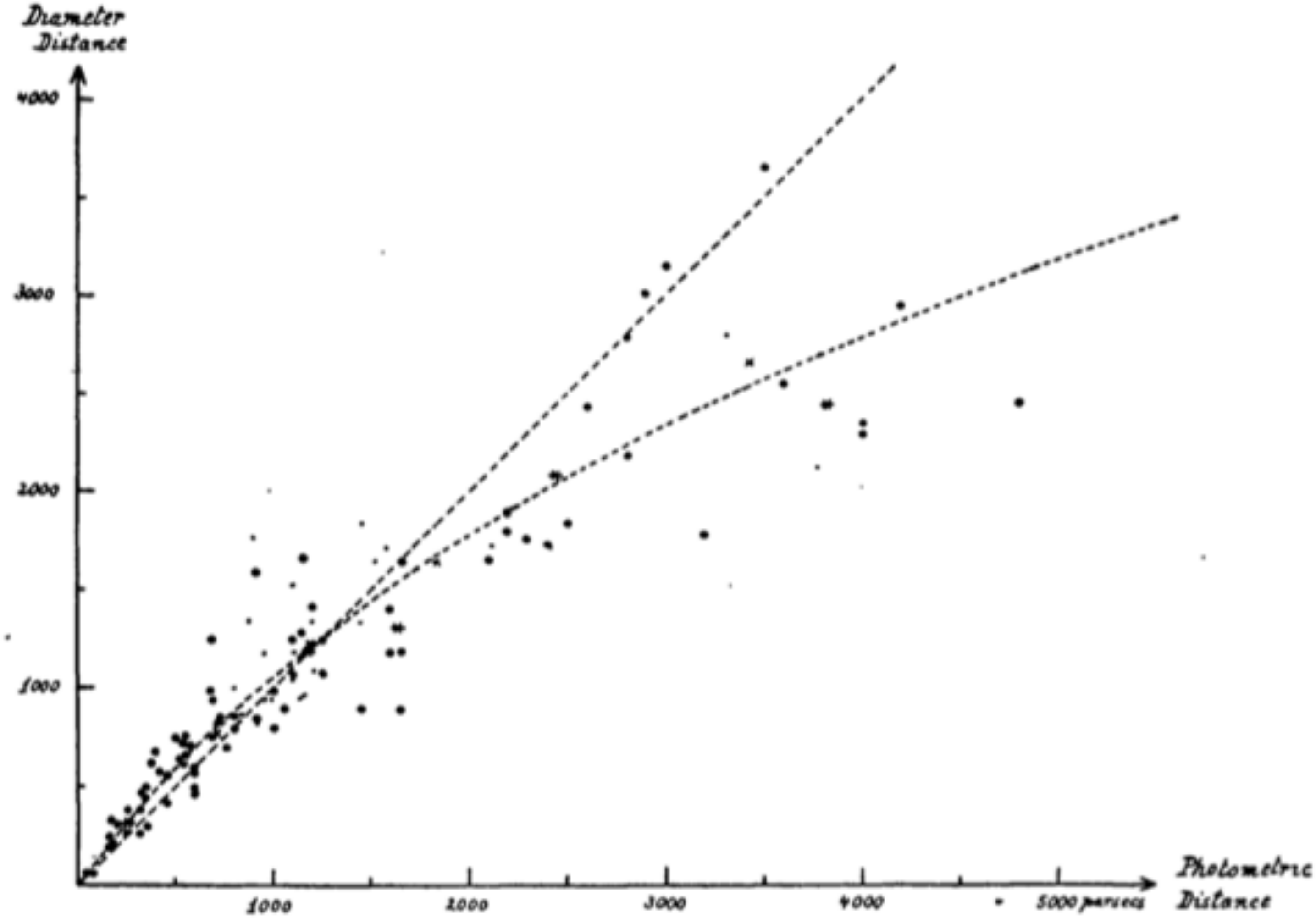


FIG. 1.—Comparison of the distances of 100 open star clusters determined from apparent magnitudes and spectral types (abscissae) with those determined from angular diameters (ordinates). The large dots refer to clusters with well-determined photometric distances, the small dots to clusters with less certain data (half weight). The asterisks and crosses represent group means. If no general space absorption were present, the clusters should fall along the dotted straight line; the dotted curve gives the relation between the two distance measures for a general absorption of $0^{m}.7$ per 1000 parsecs.

Trumpler (1930)

	Absorption Coefficients per 1000 Parsecs		
	Observed	Rayleigh Scattering	Non-selective Residual
Photographic ($\lambda = 4300$)	$\varkappa_p = 0^{\text{m}}.7$	$0^{\text{m}}.51$	$0^{\text{m}}.19$
Visual ($\lambda = 5500$)	$\varkappa_v = 0.38$	0.19	0.19
Selective absorption.....	$\varkappa_p - \varkappa_v = 0.32$	0.32	

... Rayleigh scattering. We see, thus, that our numerical results for the selective absorption cannot be traced to Rayleigh scattering by free atoms in interstellar space; they admit, however, interpretation as scattering by fine cosmic dust.

Trumpler's value of $A_V/(A_B - A_V)$=0.38/0.32=1.2 was not accurate – true value is closer to ∼3.1. But the interpretation was correct.

Where Did the Dust Come From? – Lindblad (1935)

JANUARY 26, 1935 NATURE 133

A Condensation Theory of Meteoric Matter and its Cosmological Significance

By PROF. BERTIL LINDBLAD, Director of Stockholm Observatory

IN connexion with a theory on the constitution and development of stellar systems, I have recently directed attention[1] to the significance of the great difference in temperature between the interstellar gas and solid interstellar particles as an explanation of the origin and growth of meteoric particles. If we assume with Sir Arthur Eddington[2] a temperature of 10,000° for the interstellar gas and, on account of the low energy density, a temperature of about 3° for solid particles, the latter must be assumed to grow by the condensation of sublimed matter on their surface. This conclusion is in accordance with the conclusions drawn by I. Langmuir[3] concerning the nature of the process of condensation of metallic vapours on solids. In the present case, the energy of impact of atoms on the surface of the particle will be rapidly radiated into space, or perhaps to some small extent transformed into sub-atomic energy, so that the particle remains cold. We assume that the interstellar gas actually contains all the elements in about the proportions formed in the earth's crust and in the sun, and that the

Oort & van de Hulst (1946)

BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS

1946 November 27 Volume X No. 376

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN

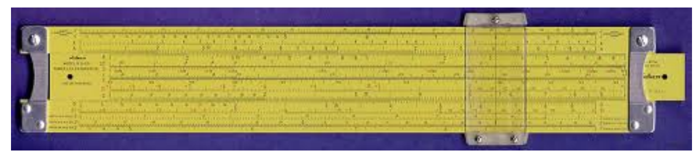
Gas and smoke in interstellar space, by *J. H. Oort* and *H. C. van de Hulst*[1]).

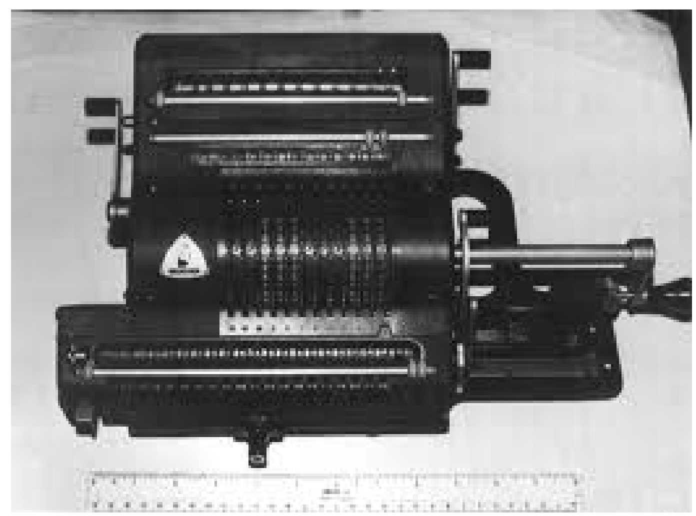
The simultaneous occurrence of the solid and gaseous phase in interstellar space in the galactic and other systems suggests that a process must be acting by which gas is released from the solid particles. Evaporation explains the presence of gaseous hydrogen and helium, but not of the other gases. Expulsion of surface atoms of these latter elements by the action of photons seems likewise insufficient. The present investigation is concerned with a third process, namely that of volatilization of solid particles by mutual encounters. Because of this volatilization particles with radii larger than the wave-length of light must be practically absent. Calculations further indicate that it is *possible* that the observed gas density is maintained in this way. The motions and forms of interstellar clouds are briefly discussed in this connection. It is probable that, in large features, the clouds of gas and the clouds of solid particles are identical. The process of melting together of colliding particles has been briefly considered.

In the sixth section the distribution function of the radii of the particles has been studied which would result if an equilibrium between gas and solid particles were maintained by the processes of sublimation and of evaporation through collisions. The distribution is characterized by a steep drop, beginning at a radius between one and one-tenth time the wave-length of light (Figure 4 and Table 2).

Oort & van de Hulst (1946)

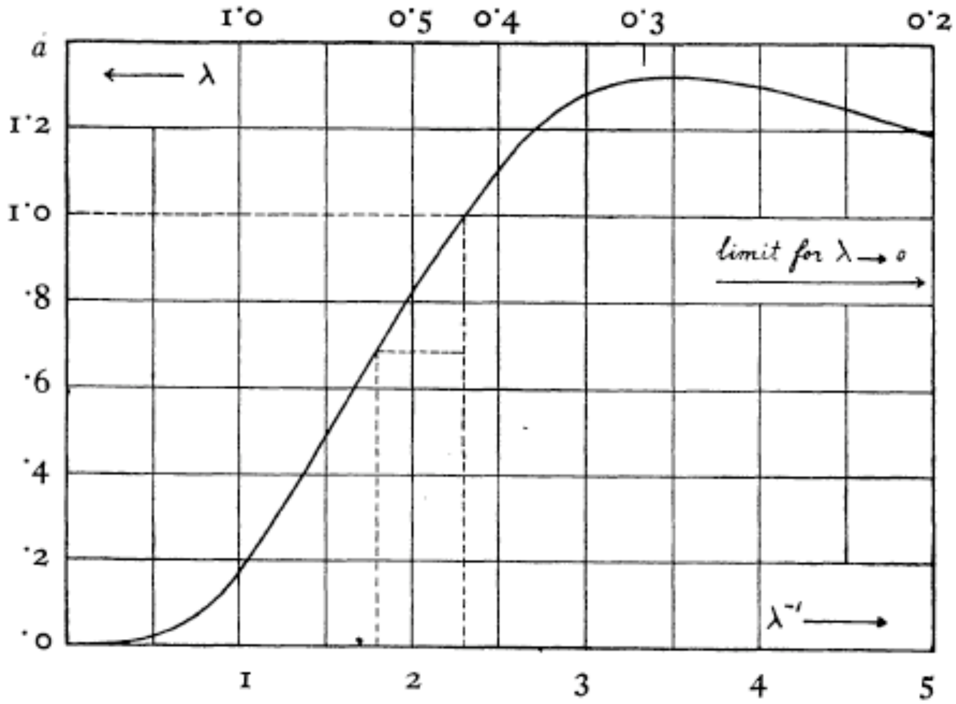
- Mie theory for scattering and absorption by spheres
- Calculate reddening produced by size distribution
- Done during WWII
  Computationally intensive.
  Computational resources:





Oort & van de Hulst (1946)

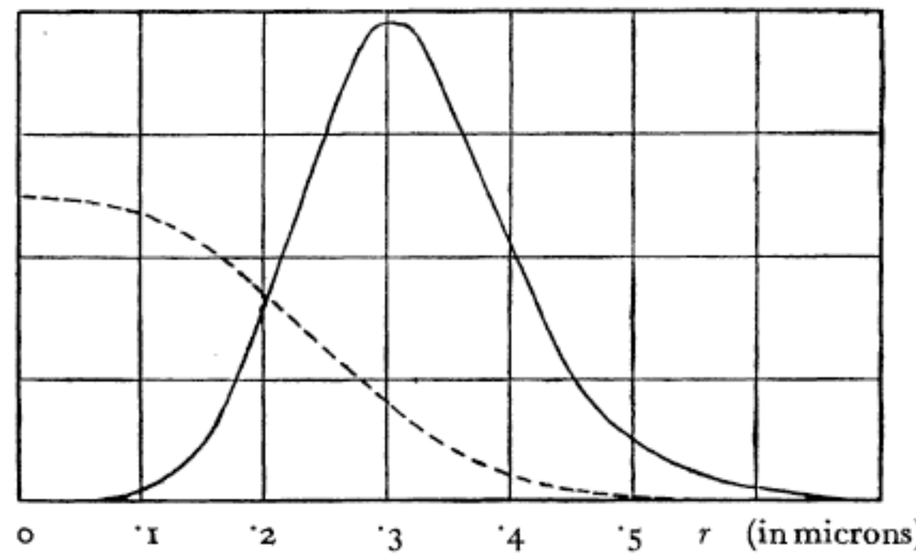
FIGURE 8



Computed interstellar extinction coefficient *a*, in mag/kps, as a function of 1/λ, if the scales of the co-ordinates are fixed according to (44) and (45). The dotted lines indicate the visual and photographic absorptions.

- Oort & van de Hulst (1946) attempted to **predict** dust size distribution from formation/destruction balance.
  Many assumptions...

FIGURE 9



Relative contribution of particles of various sizes to the total photographic scattering (full curve). The dotted curve shows the distribution function of the radii.

- Typical particle radius $\sim 0.1\mu$m, sharp fall-off for larger sizes.
  We still think this.
- Relatively few small grains ($dn/da \approx const$ for $a \lesssim 0.1\mu$m).
  Problem: no measurements of UV extinction in 1946!
  Today we think that there are many more small grains.

Polarization of Starlight

- Aim: to measure polarization of light from distorted stellar atmospheres in close binaries. (Polarization should depend on phase of binary orbit.)
- Instrumentation check: observe ordinary stars, which should emit unpolarized light
- *Surprise!:* light from ordinary stars is polarized! (Hiltner 1949; Hall 1949)

February 18, 1949, Vol. 109 SCIENCE 165

Polarization of Light From Distant Stars by Interstellar Medium

W. A. Hiltner
Yerkes Observatory, University of Chicago

166 SCIENCE February 18, 1949, Vol. 109

Observations of the Polarized Light From Stars

John S. Hall
U. S. Naval Observatory, Washington, D. C.

Polarization of Starlight

- Polarization correlated with $E(B-V)$
- Stars nearby on sky have similar direction of polarization

- ISM is a *polarizer*!
  - new property of space?
  - **aligned dust grains acting as a polarizer?**

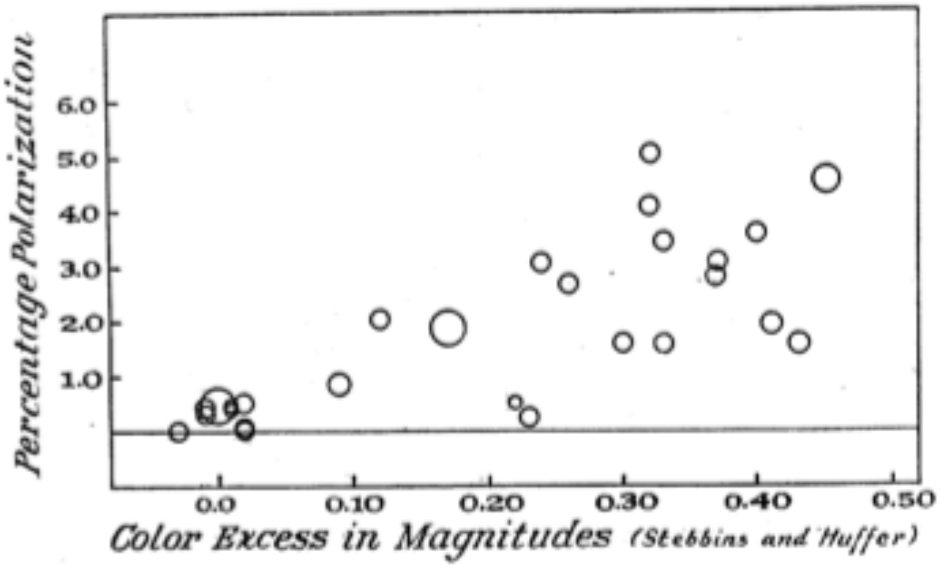


FIG. 3. Observational evidence of a correlation between color excess and percentage of polarization for early-type stars. The size of the circle indicates the weight of the observations.

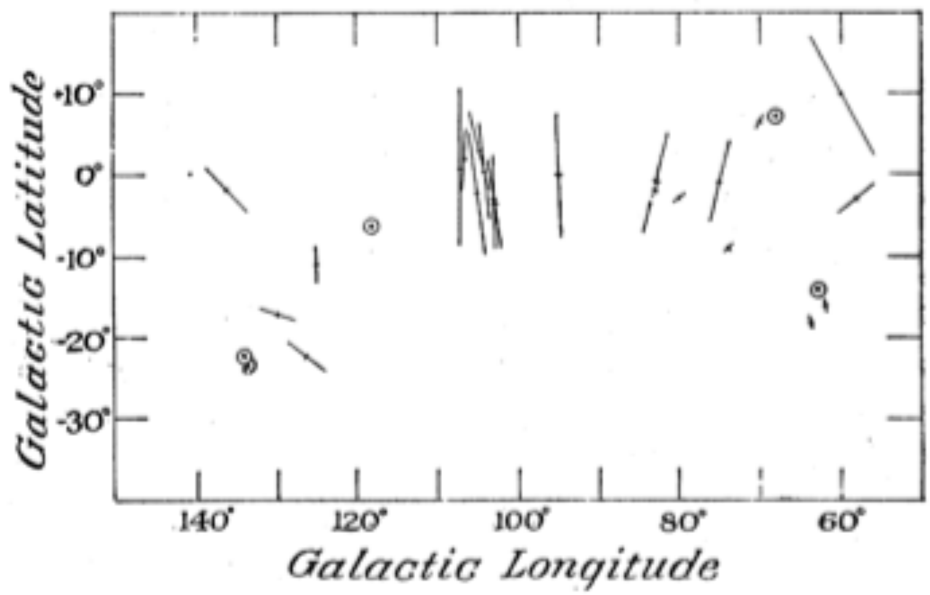


FIG. 4. Observational evidence that there is no one preferential orientation of the plane of polarization. Stars showing no polarization are represented by circles.

- *Several theoretical papers in 1949-51 trying to explain alignment of interstellar dust... some wildly incorrect.*

Alignment problem remains challenging....

Developments in the 1960s and 70s: UV and IR

Balloons (e.g., Stratoscope II, 1971)
Interstellar grains are *not* H_2O ice!
(Danielson et al. 1965)

Aircraft in Stratosphere
NASA Learjet, 30cm telescope, 1968-
IR absorption and emission features

Sounding rockets (suborbital)
Discovery of 2200Å extinction feature (Stecher 1965) and rising extinction in vacuum UV (Stecher 1969).

OAO-2 (1968-1973)
OAO-3 (Copernicus: 1972-1981)
IUE (1978-1996)
thorough studies of UV extinction curves

Where Does the Dust Come From?

- Pickering (1897), Kapteyn (1909a), Trumpler (1930):
  "meteoric matter" of unknown origin.

- Lindblad (1935) proposed grain growth by accretion in ISM, and in dense star-forming regions.
  Further elaborated by Oort & van de Hulst (1946), with H_2O ice expected to be important grain constituent.

Where Does the Dust Come From? 2.

- Hoyle & Wickramasinghe (1962) proposed formation of graphite in the atmospheres of cool carbon stars.
- Seemingly supported by discovery of 2200Å extinction feature in UV spectroscopy from rockets:

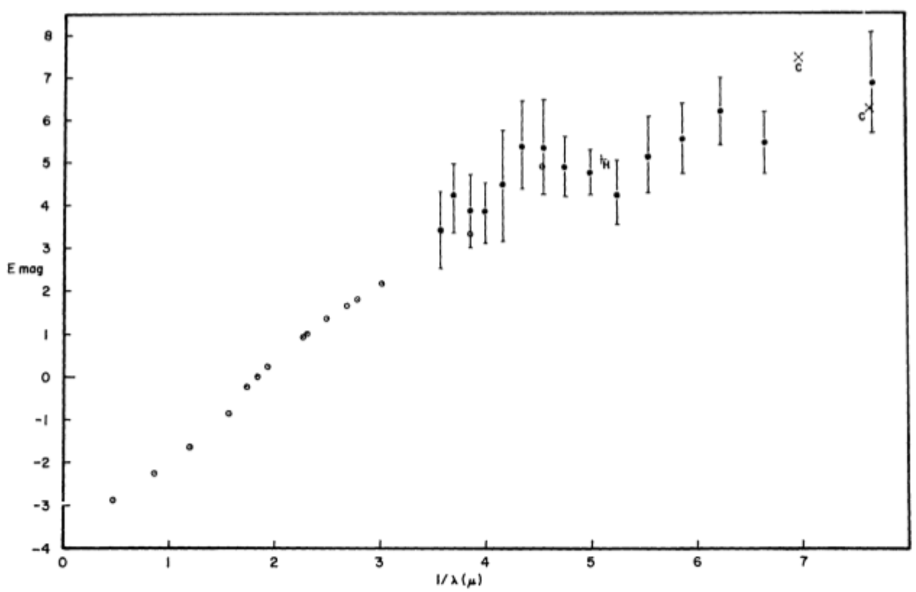


FIG. 1.—The observed mean value for interstellar extinction. *Large solid dots:* mean values for interstellar extinction and their mean errors for up to five pairs of stars as a function of inverse wavelength. *Open circles:* Boggess and Borgman (1964) The point marked "*H*" is from Alexander *et al.* (1964). The points marked "*C*" are from Chubb and Byram (1963). All values are normalized to $B - V = 1$ and $V = 0$.

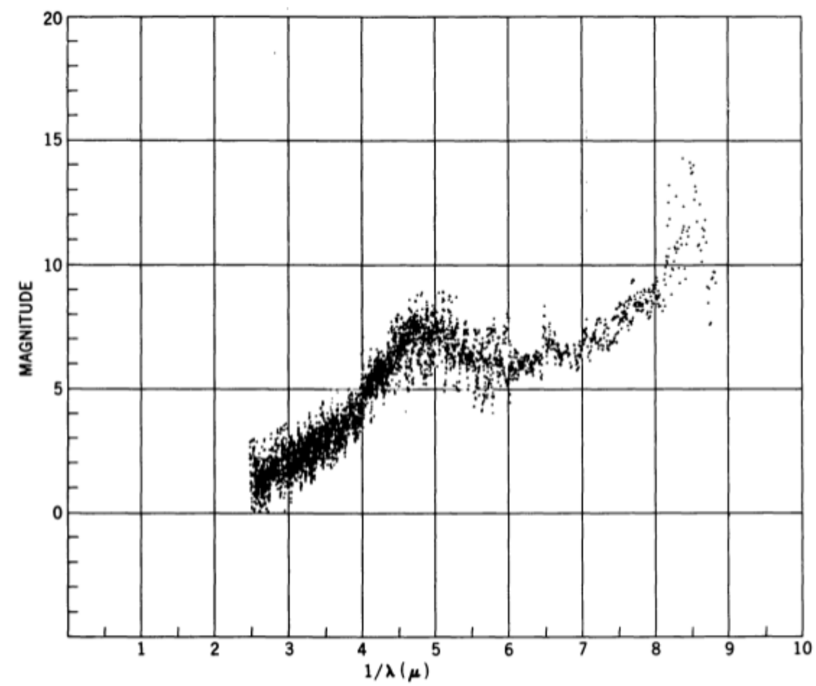


FIG. 1.—Interstellar extinction in magnitudes as a function of inverse wavelength determined from ζ and ε Per. Curve is normalized to $B - V = 1$ mag and $V \sim 0$.

Stecher (1965) Stecher (1969)

- Small graphite spheres expected to produce absorption peak matching the observed 2200Å feature (Stecher & Donn 1965).

Where Does the Dust Come From? 3.

- Gillett et al. (1968) measured (from ground) first mid-IR spectra of M giants and supergiants:

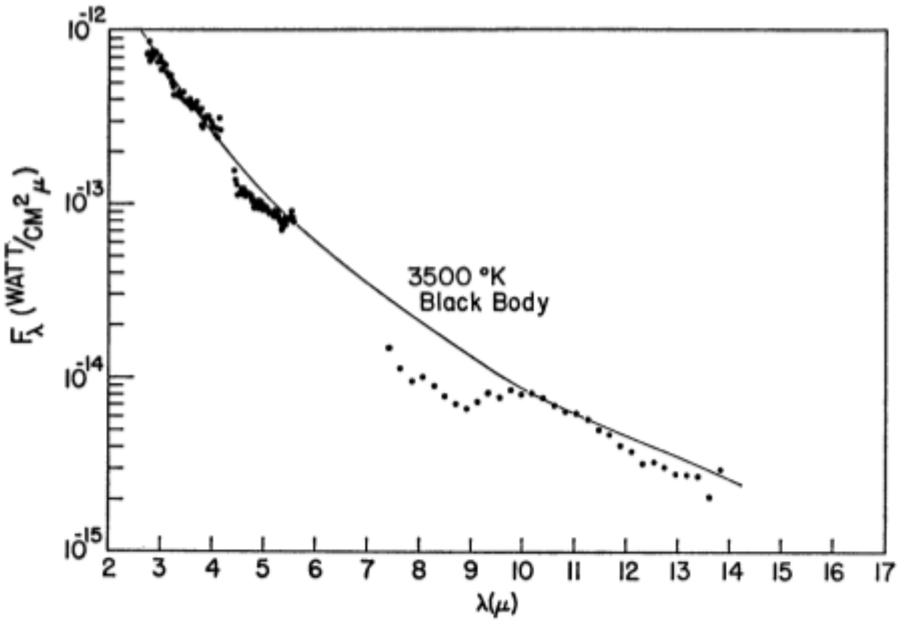


FIG. 5.—Spectrum of α Ori

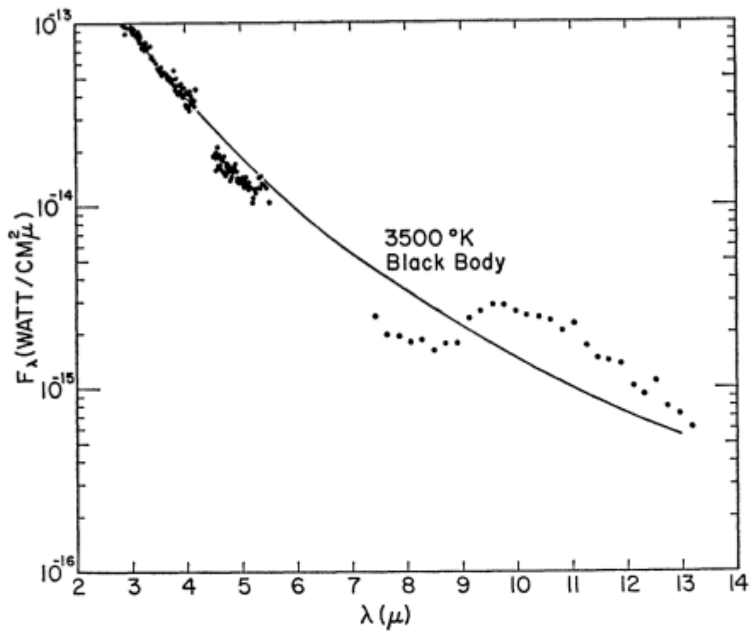


FIG. 6.—Spectrum of μ Cep

Discovered 10μm emission feature in α Ori (Betelgeuse; M2 Iab), μ Cep (M2 Ia), o Cet (Mira; M6-M9), and χ Cyg (M7). No identification made.

- Larimer (1967) discussed condensation in cooling gas of solar composition, and Gilman (1969) applied this to M giants.
- Woolf & Ney (1969) proposed **silicate grains** as source of 10μm emission feature in spectra of giants later than M5, and supergiants later than M2.

Characteristics of Interstellar Dust as of 1975

- General view: interstellar dust is "stardust":
  - silicates from cool stars with O/C > 1
  - graphite from cool carbon stars (C/O > 1)
- size distribution:
  - Most of mass in $0.1 < a < 0.3\,\mu\mathrm{m}$ particles
    (these particles dominate the optical-IR extinction, and account for scattering in reflection nebulae)
  - Most of the surface area in small $a \lesssim 0.02\,\mu\mathrm{m}$ particles
    (to account for rise in extinction in UV)
  - Some of the $a \lesssim 0.02\,\mu\mathrm{m}$ particles are graphite
    (to account for the 2200Å extinction feature)
- Particles are nonspherical and somehow aligned to produce polarization of starlight
- Particles are expected to be heated to $\sim$20K by interstellar starlight, should radiate near $\sim 100\mu\mathrm{m}$

Next 2 Talks

2. Modern Observations of Interstellar Dust

- Extinction
- Scattering of Optical Light
- Scattering of X-Rays
- IR Spectroscopy
- Diffuse Interstellar Bands
- IR Emission
- Microwave Emission
- X-Ray Spectroscopy
- Presolar Grains
- Grains Entering the Heliosphere

3. Theoretical Studies of Interstellar Dust

- Interstellar Extinction and Polarization
- Scattering Properties
- Heating/Cooling of Grains and IR Emission
- Rotational Dynamics and "Spinning Dust" Emission
- Grain Destruction in the ISM
- Implications for Grain Evolution in ISM


THANK YOU

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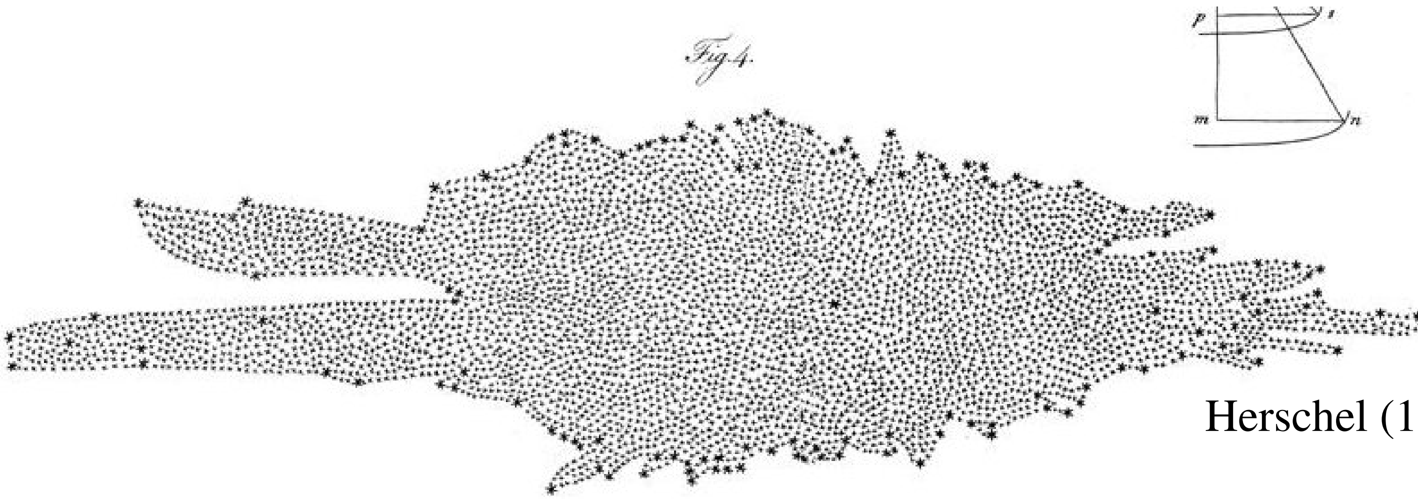
On the Construction of the Heavens



Herschel (1785)

Trumpler (1930)

Our Milky Way system seems to contain a considerable amount of finely divided matter, noticeable by its absorption of light. This matter appears to be made up mainly of:

1. Free atoms (*Ca, Na,* and probably others) causing interstellar (stationary) absorption lines observable in the spectra of distant stars. Eddington estimates their space density of the order of 10^{-24} grams per cubic centimeter (one H atom per cubic centimeter) and shows that this is not sufficient to originate an observable amount of Rayleigh scattering.

2. Free electrons are likely to be included, since the observed interstellar calcium atoms are ionized.

3. Fine cosmic dust particles of various sizes (average mass of particle 10^{-19} grams or larger, space density of the order of 10^{-23} grams per cubic centimeter) maintained in space by light pressure of the stars and producing the observed selective absorption by Rayleigh scattering.

4. Perhaps we should add also larger meteoric bodies, obstructing light of all wave-lengths equally, which may be responsible for a small part of the general absorption (residual effect).

Trumpler (1930)

This absorbing medium is limited to our galactic system, forming an essential feature of it; it is much concentrated to the galactic plane extending along the latter like a thin disk probably not more than a few hundred parsecs thick. While its distribution follows the Milky Way in general, it is not necessarily uniform. The observed obscuration of globular clusters and spiral nebulae near the galactic circle then follows