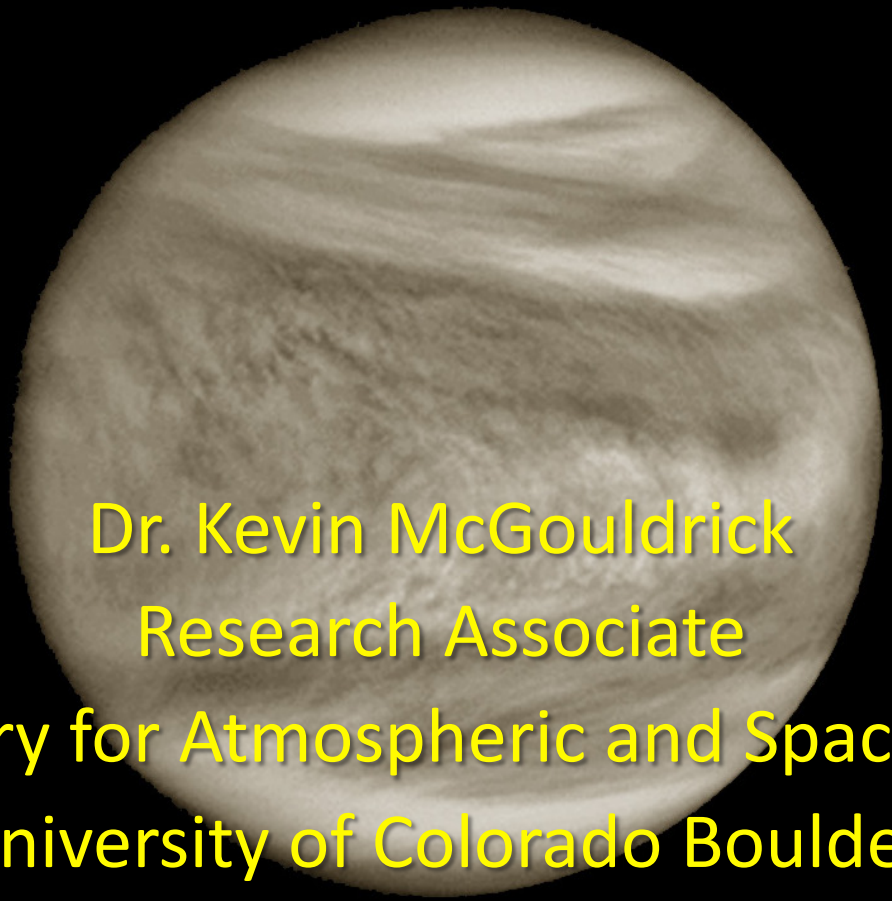
# Learning from the Transits of Venus
## 18 June 2012



Dr. Kevin McGouldrick
Research Associate
Laboratory for Atmospheric and Space Physics
University of Colorado Boulder

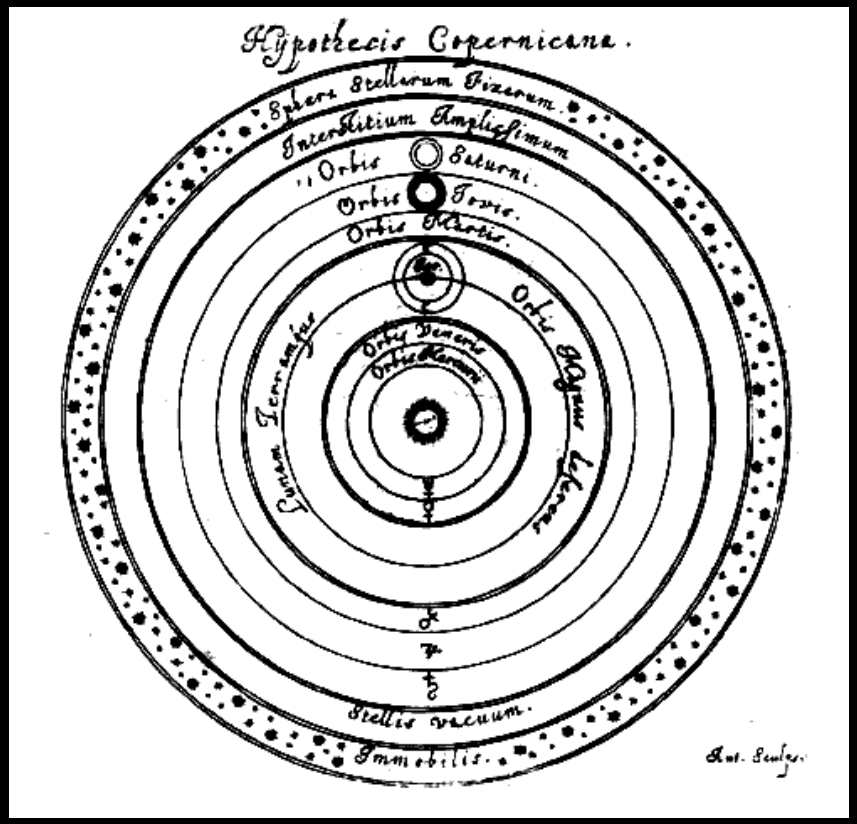
Image Courtesy NASA

# Venus Tablet of Ammisaduqa

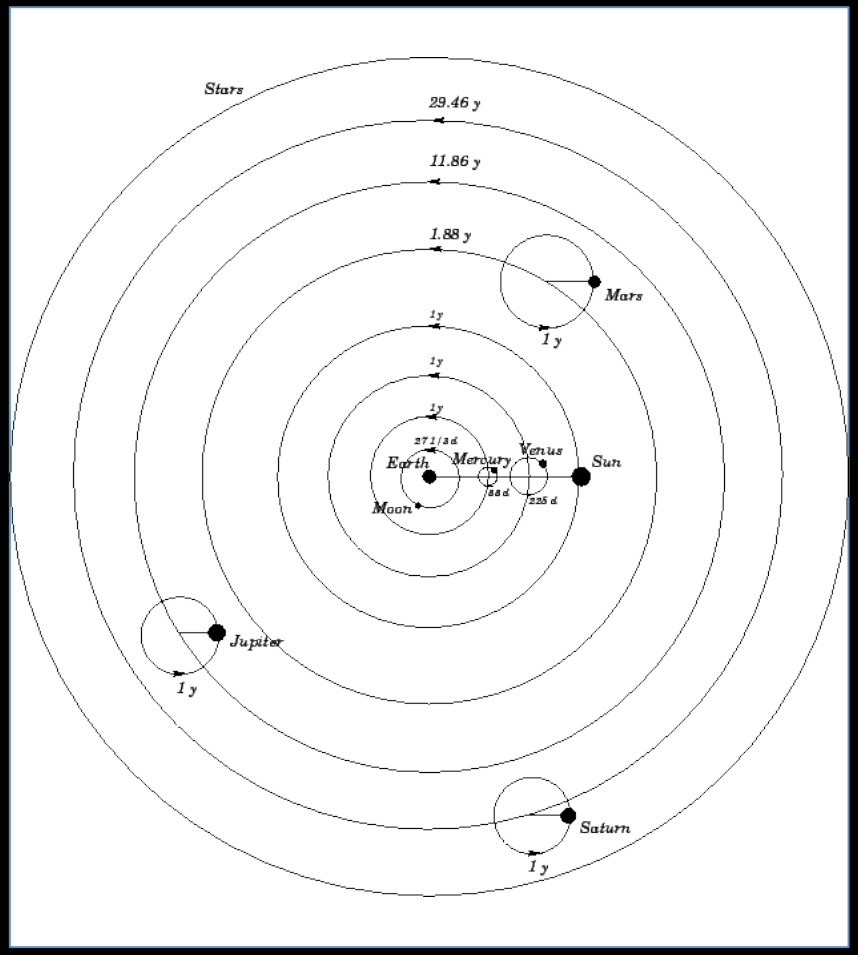
- Dates to 17th C. BC
- May be oldest known recorded astronomical observation

Source/Photographer: Fæ (Own work)

# Copernicus versus Ptolemy



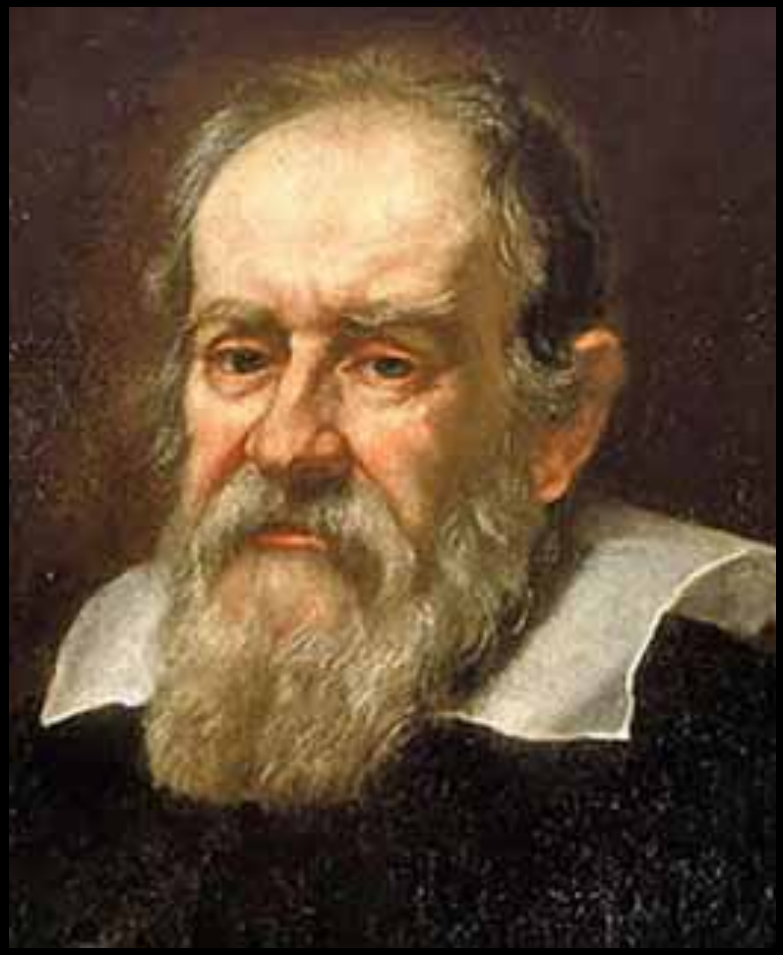

1543



# Copernicus versus Ptolemy

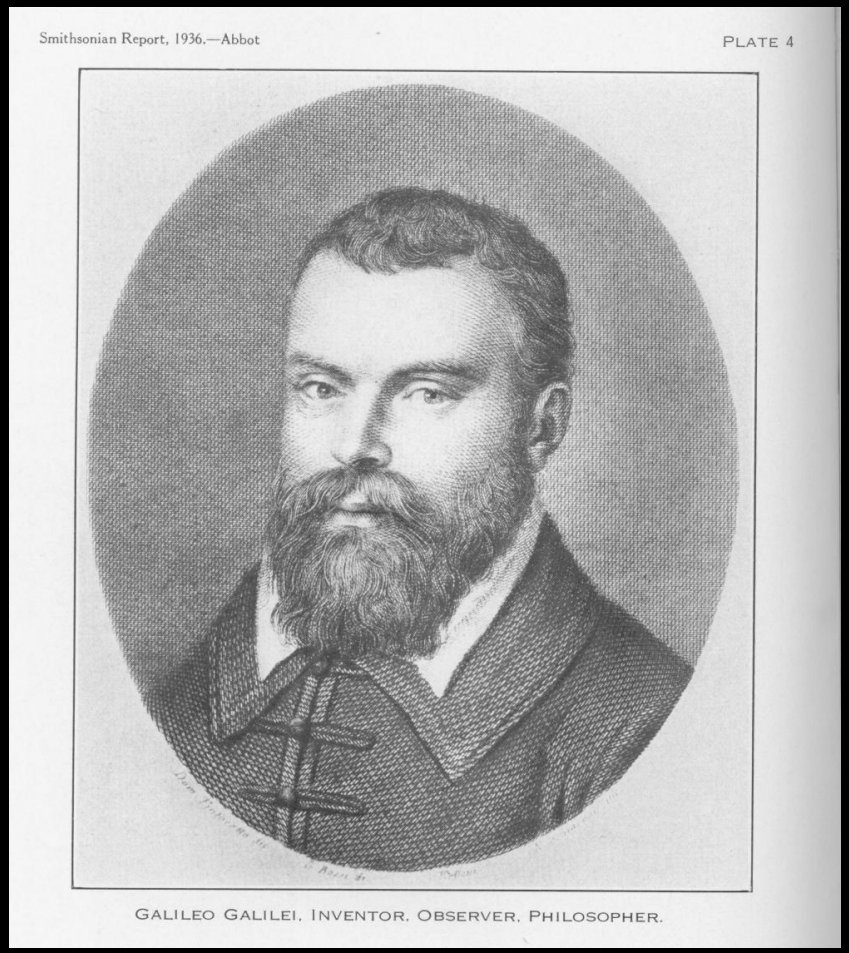
- "It does not make any difference how beautiful your guess is. It does not make any difference how smart you are, who made the guess, or what his name is – if it disagrees with experiment it is wrong. That is all there is to it."
  - Richard Feynman
- Science is quite simple:
  - Observe phenomena
  - Make a guess to explain what we see
  - Make predictions based on that guess
  - Compare predictions with new observations

# Galileo and Heliocentrism



- Galileo was staunch Copernican.
- Learned of telescope invention in 1609.

# Galileo and Heliocentrism

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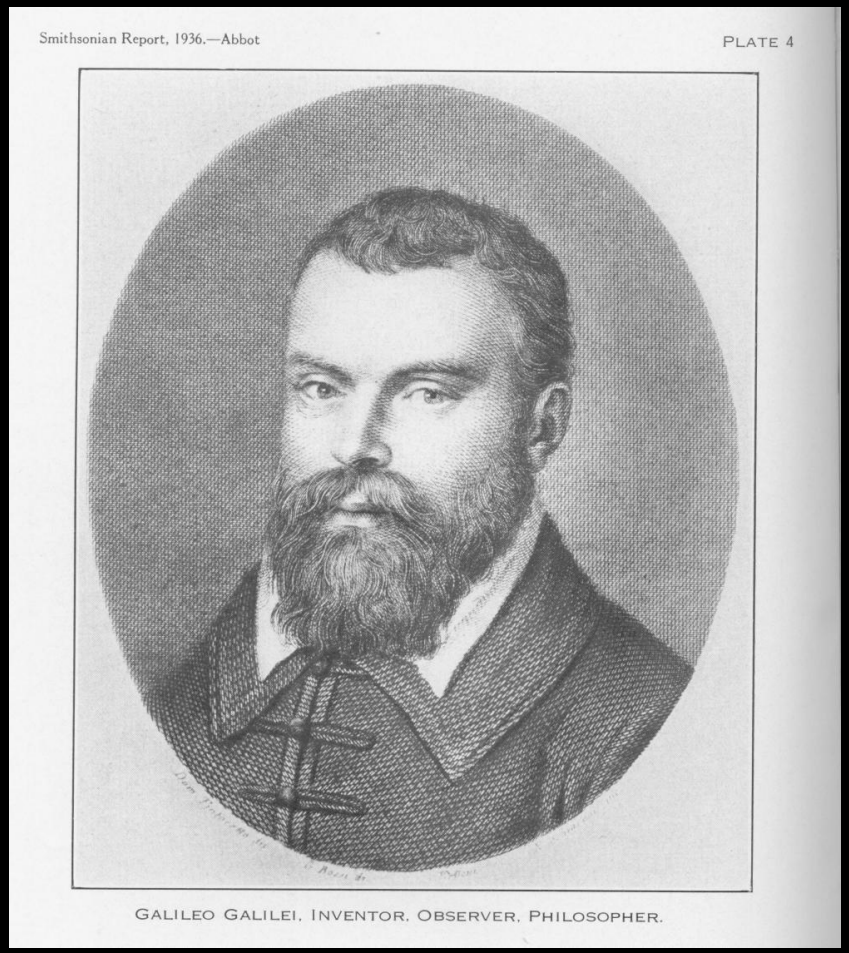


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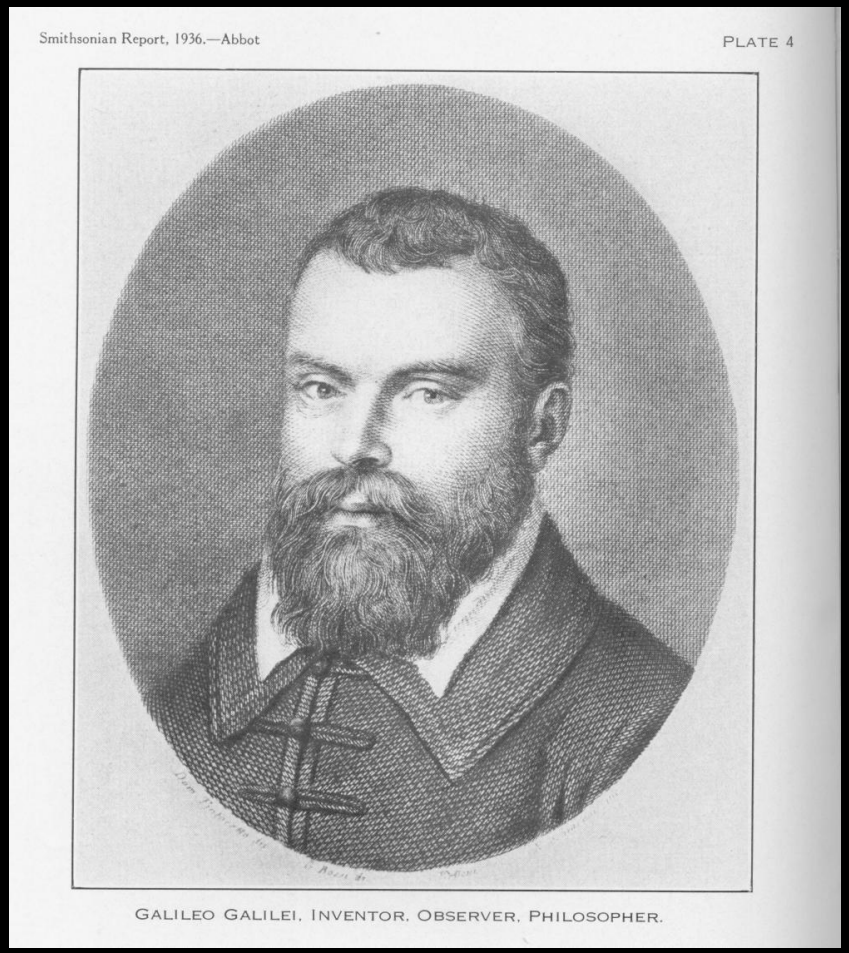
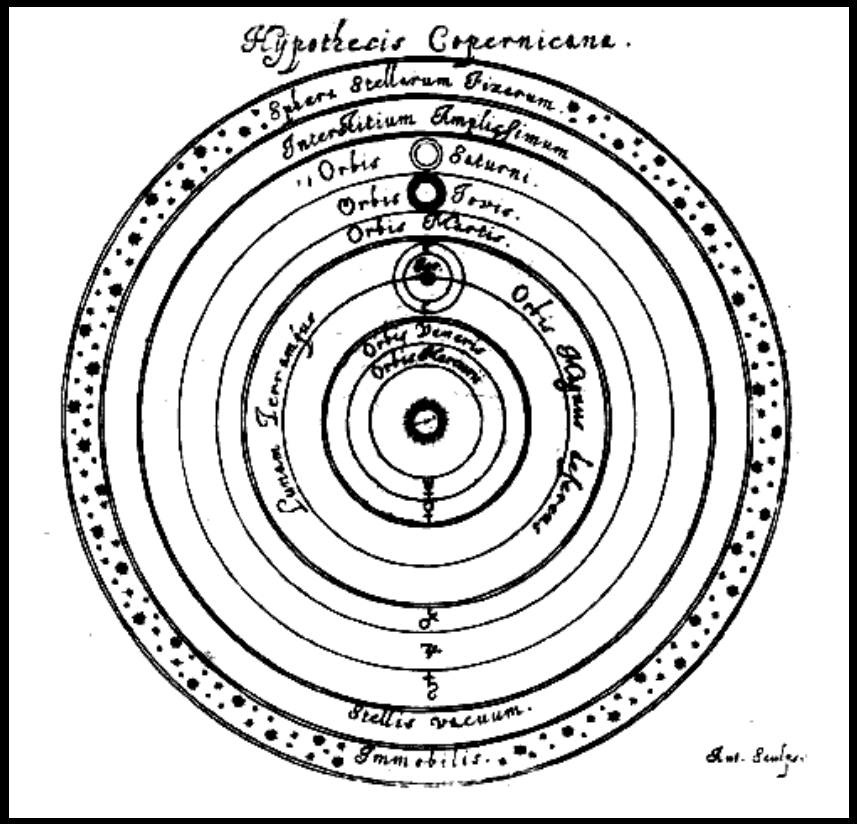
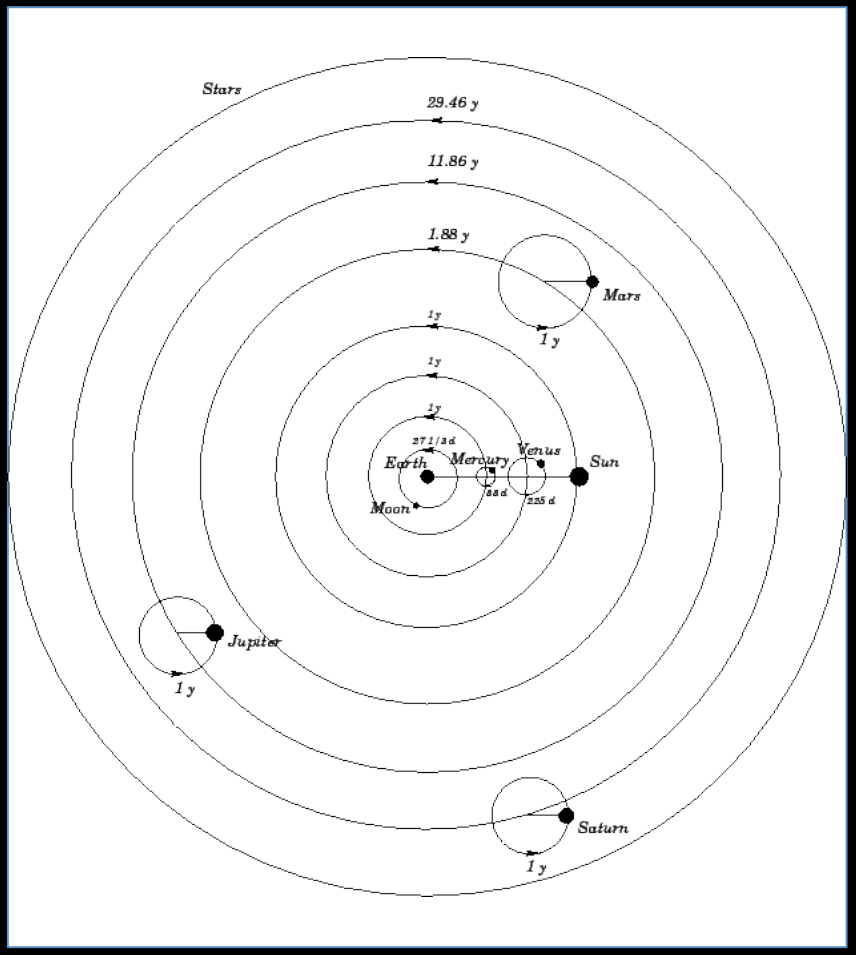
# Galileo and Heliocentrism




- Galileo was staunch Copernican.
- Learned of telescope invention in 1609.
- Built one and observed Jupiter: discovered moons
- Knew he had found a tool that could settle the Geo/Helio dispute.

# Copernicus versus Ptolemy



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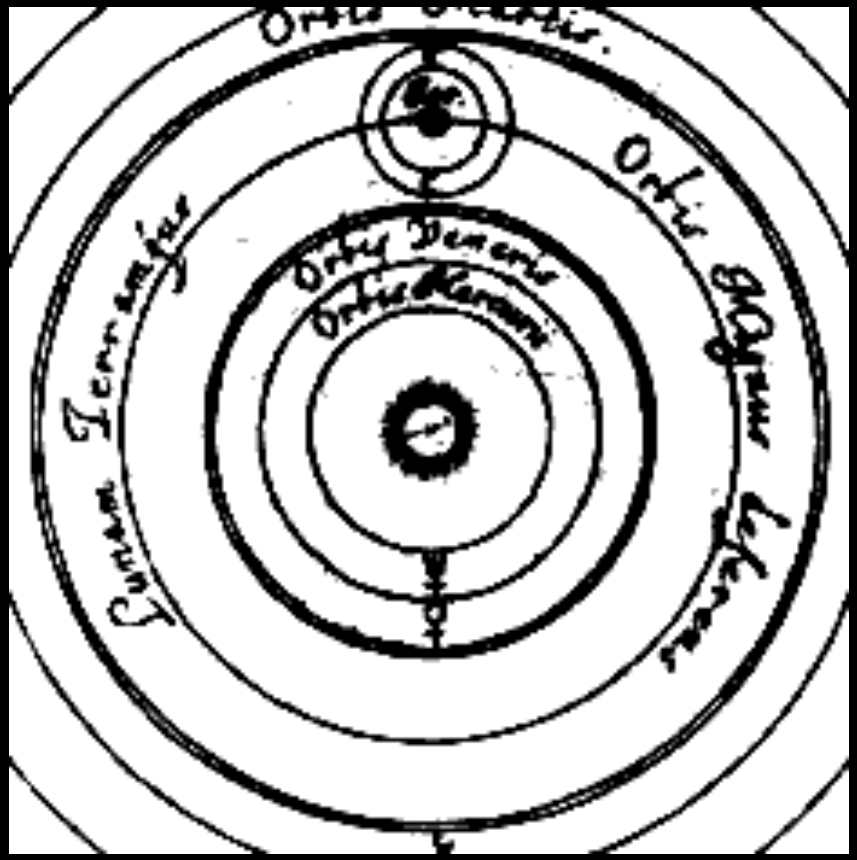
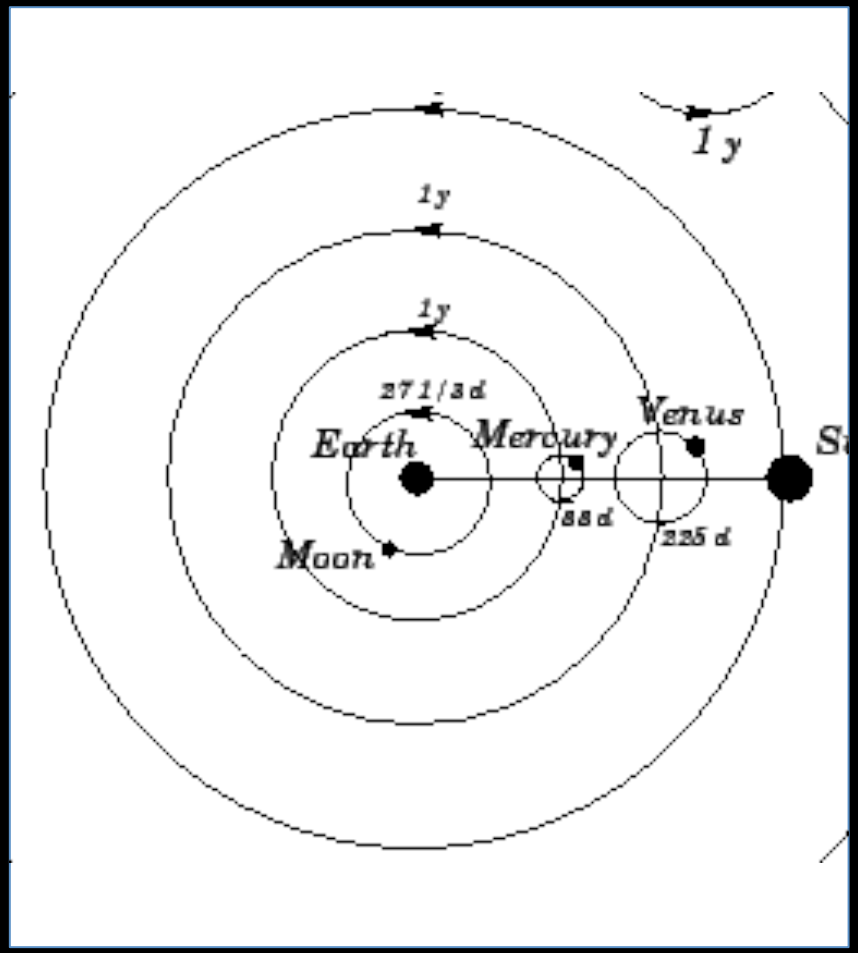
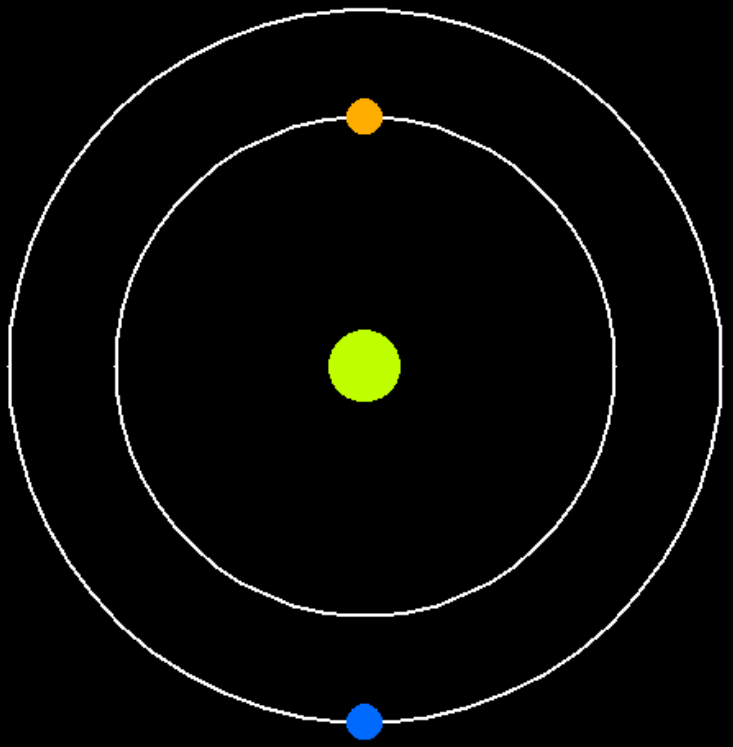




# Cynthiae figuras aemulatur mater amorum!



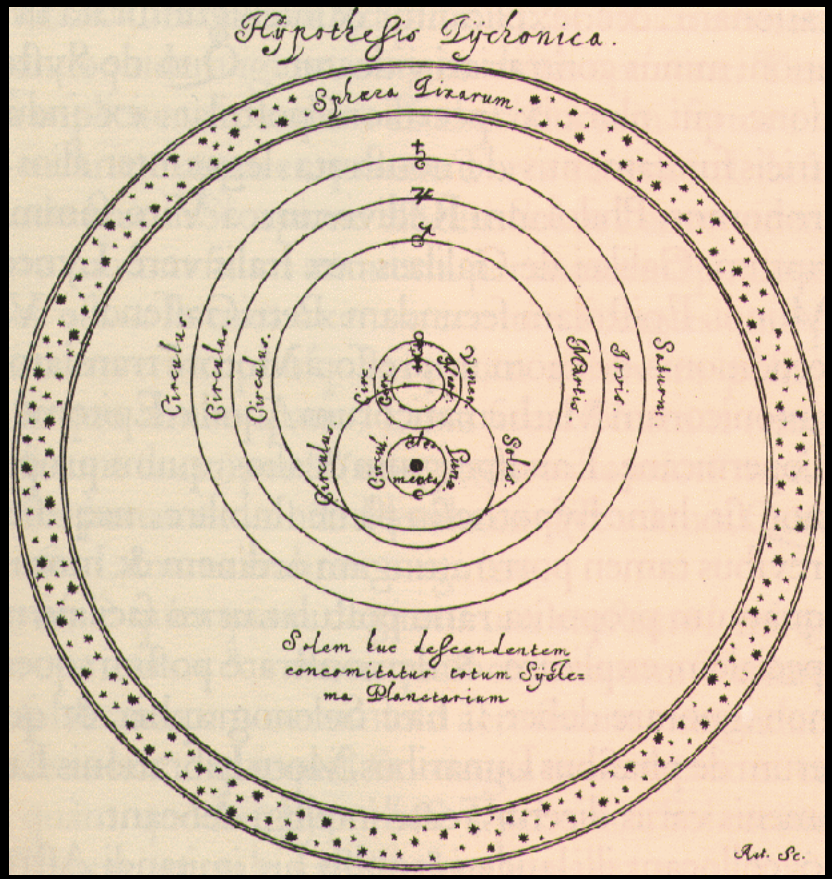
# You can be Galileo!

| Date | % illuminated | Angular size (") | Distance (AU) | Angle: Sun-Planet-Earth |
|---|---|---|---|---|
| 9/1/12 | 58 | 20 | 0.84 | 80 |
| 10/1/12 | 71 | 16 | 1.06 | 65 |
| 11/1/12 | 81 | 13 | 1.26 | 52 |
| 12/1/12 | 88 | 12 | 1.42 | 40 |
| 1/1/13 | 94 | 11 | 1.55 | 29 |
| 2/1/13 | 97 | 10 | 1.65 | 19 |
| 3/1/13 | 99 | 10 | 1.70 | 10 |
| 4/1/13 | 100 | 10 | 1.72 | 2 |
| 5/1/13 | 99 | 10 | 1.70 | 12 |
| 6/1/13 | 96 | 10 | 1.62 | 24 |

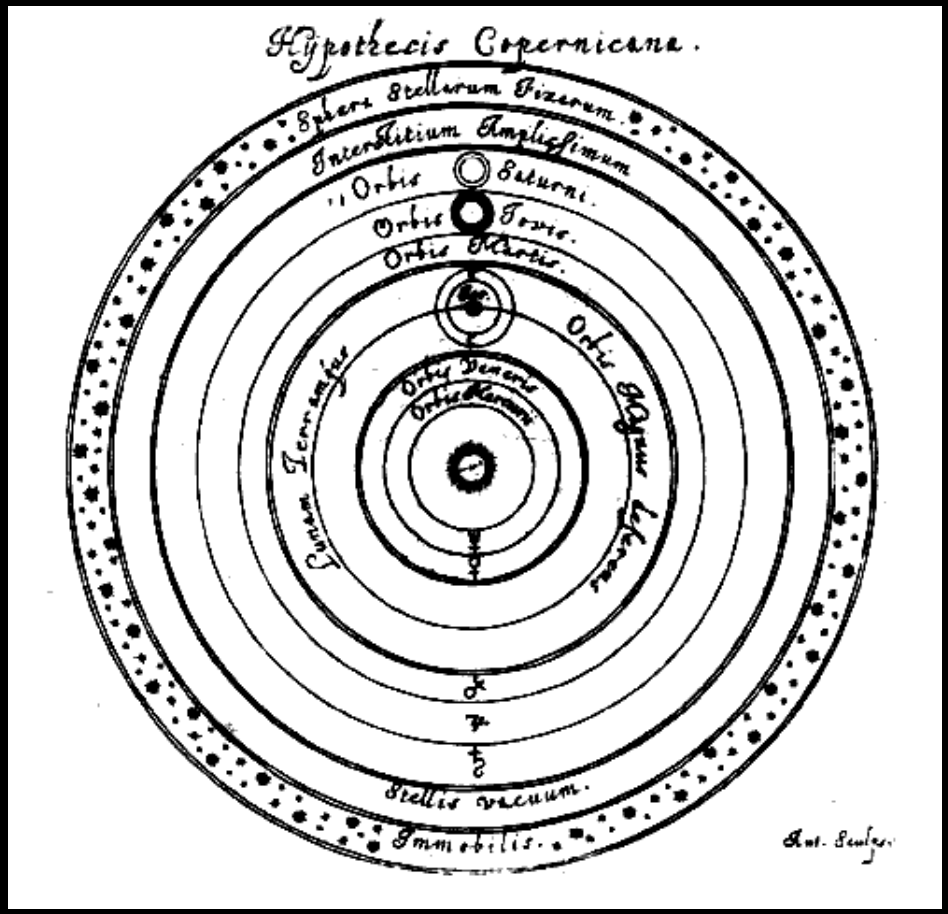
| Date | % illuminated | Angular size (") | Distance (AU) | Angle: Sun-Planet-Earth |
|---|---|---|---|---|
| 7/1/13 | 90 | 11 | 1.50 | 36 |
| 8/1/13 | 83 | 13 | 1.33 | 49 |
| **9/1/13** | **74** | **15** | **1.12** | **62** |
| **10/1/13** | **63** | **18** | **0.91** | **75** |
| **11/1/13** | **50** | **25** | **0.67** | **90** |
| **12/1/13** | **31** | **37** | **0.45** | **113** |
| **1/1/14** | **4** | **60** | **0.28** | **157** |
| **2/1/14** | **13** | **51** | **0.33** | **138** |
| 3/1/14 | 36 | 33 | 0.51 | 106 |

JPL Horizons: http://ssd.jpl.nasa.gov/?horizons

# Tycho Brahe's Solar System

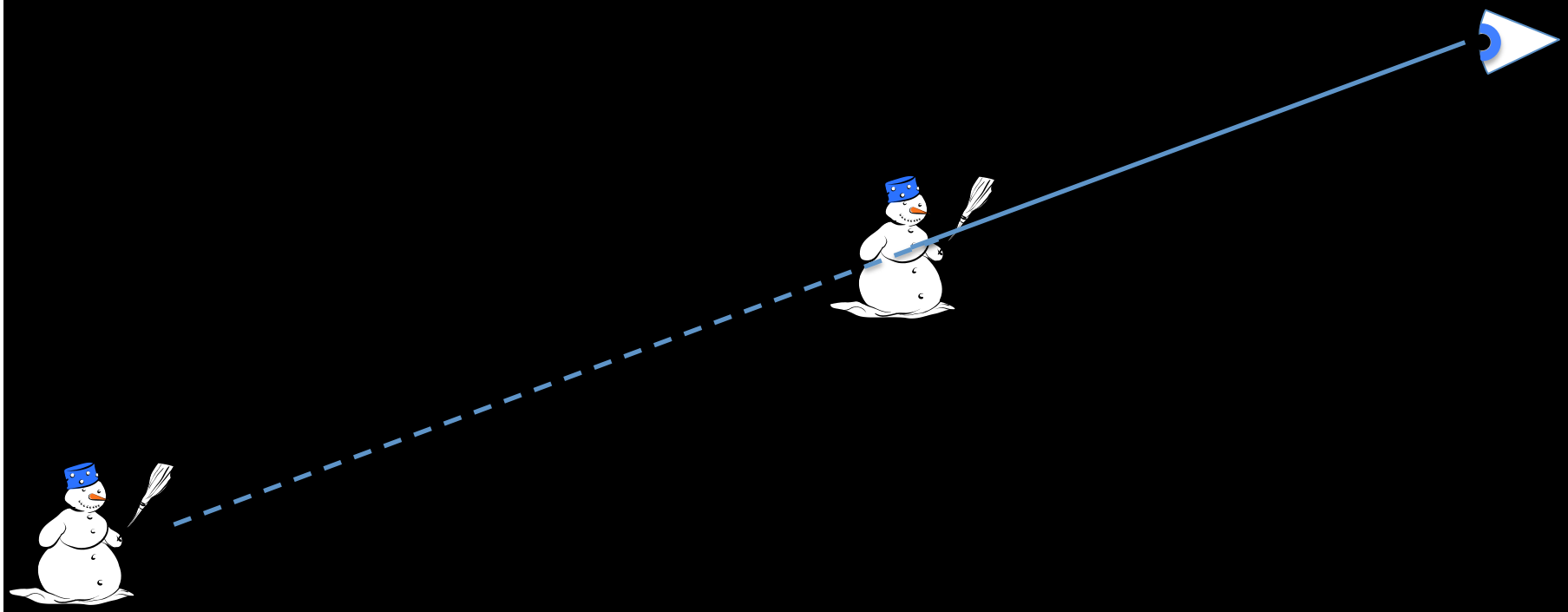



1601




1543

# Parallax



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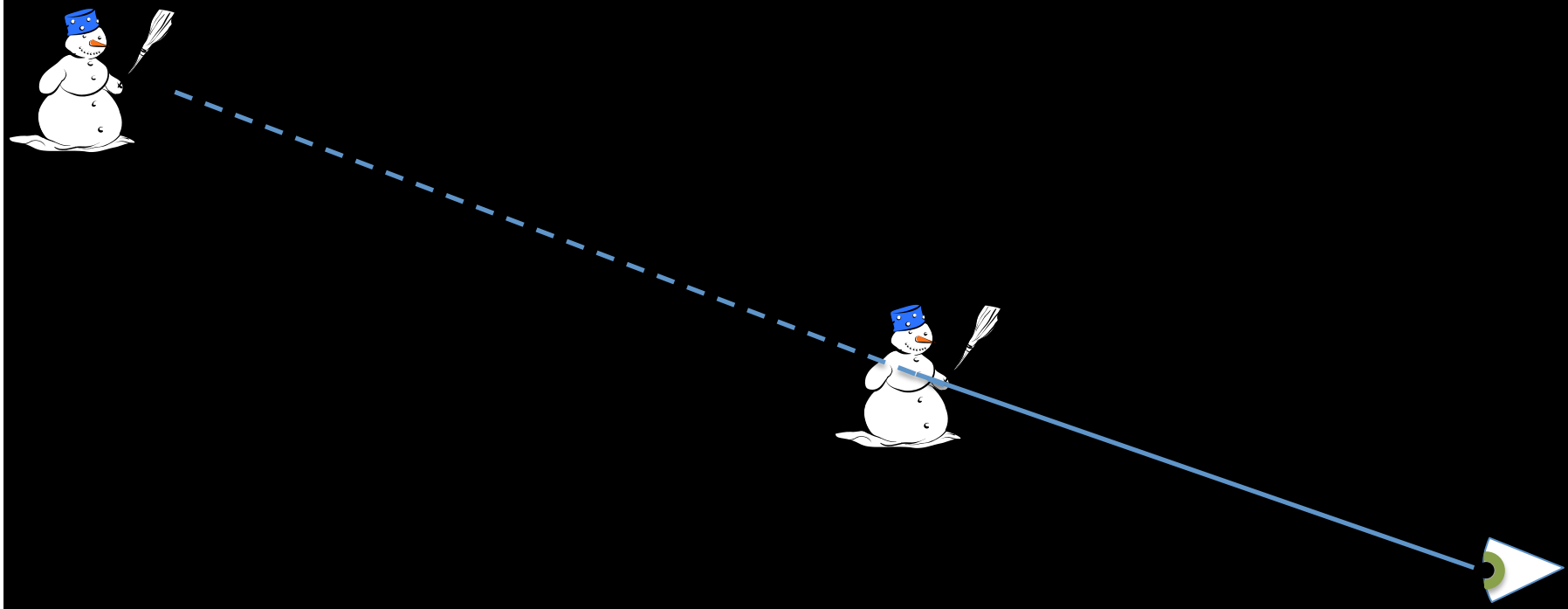

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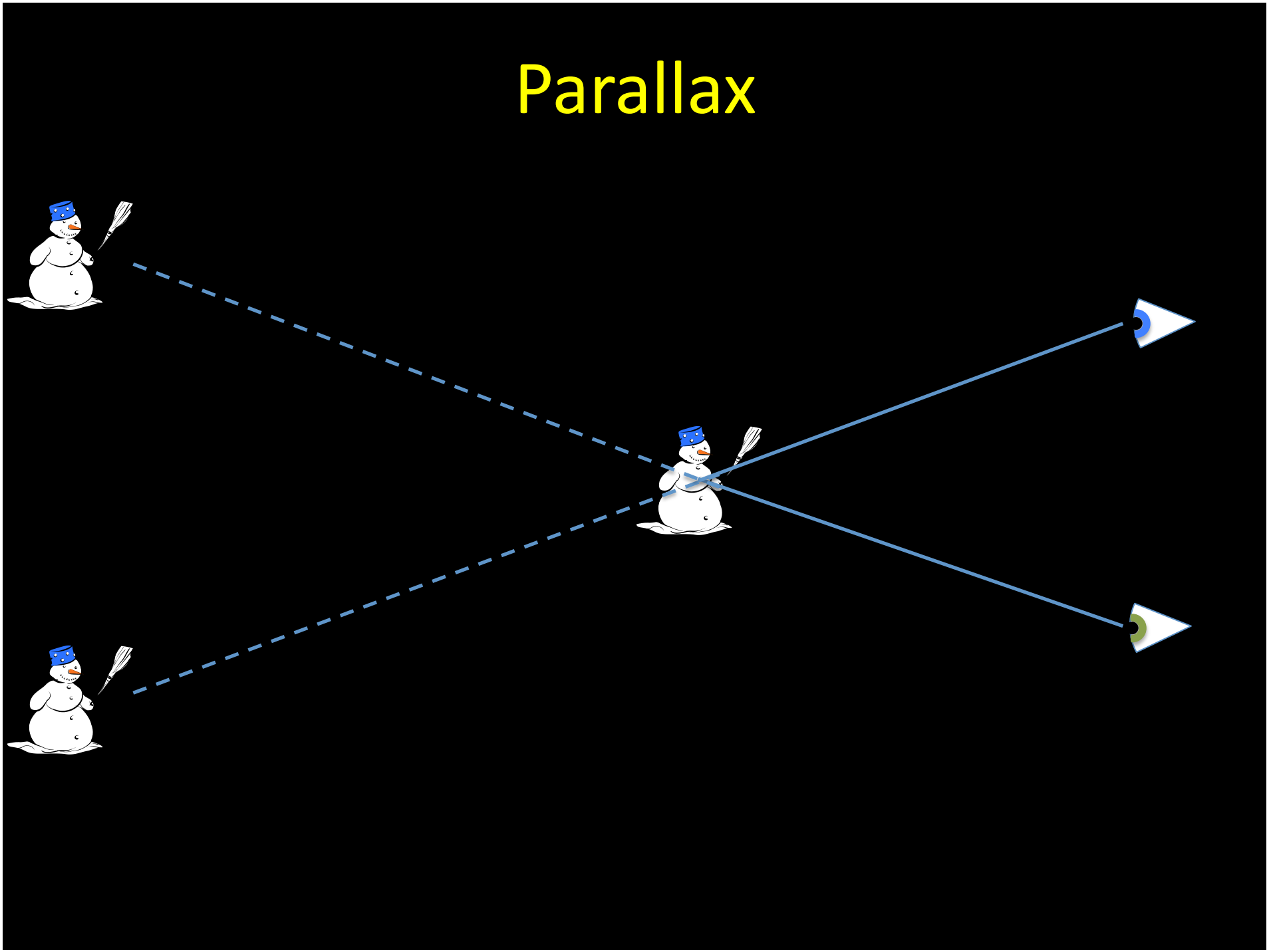

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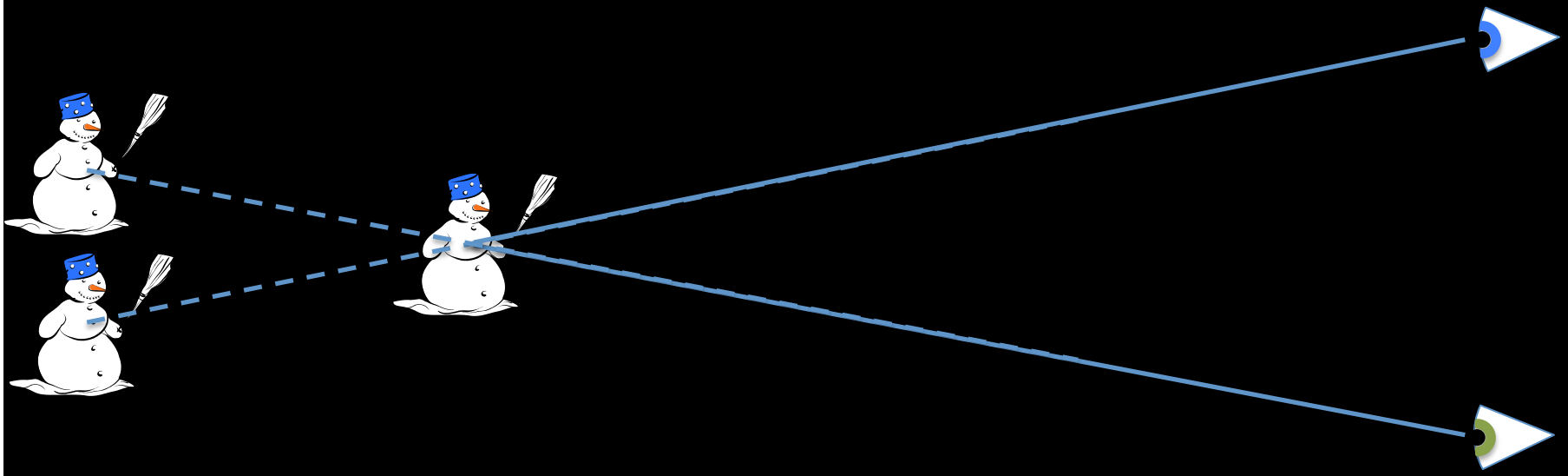

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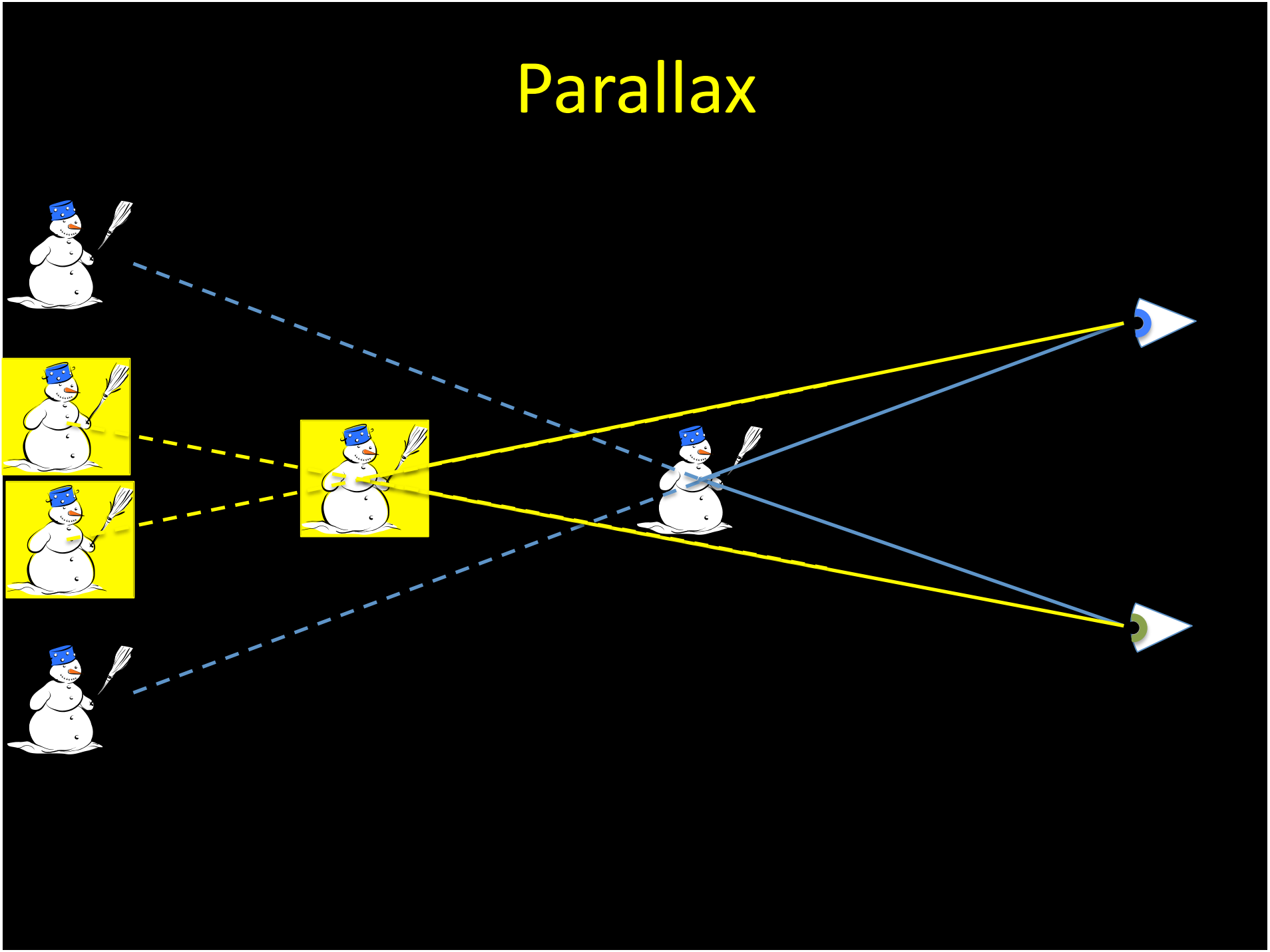

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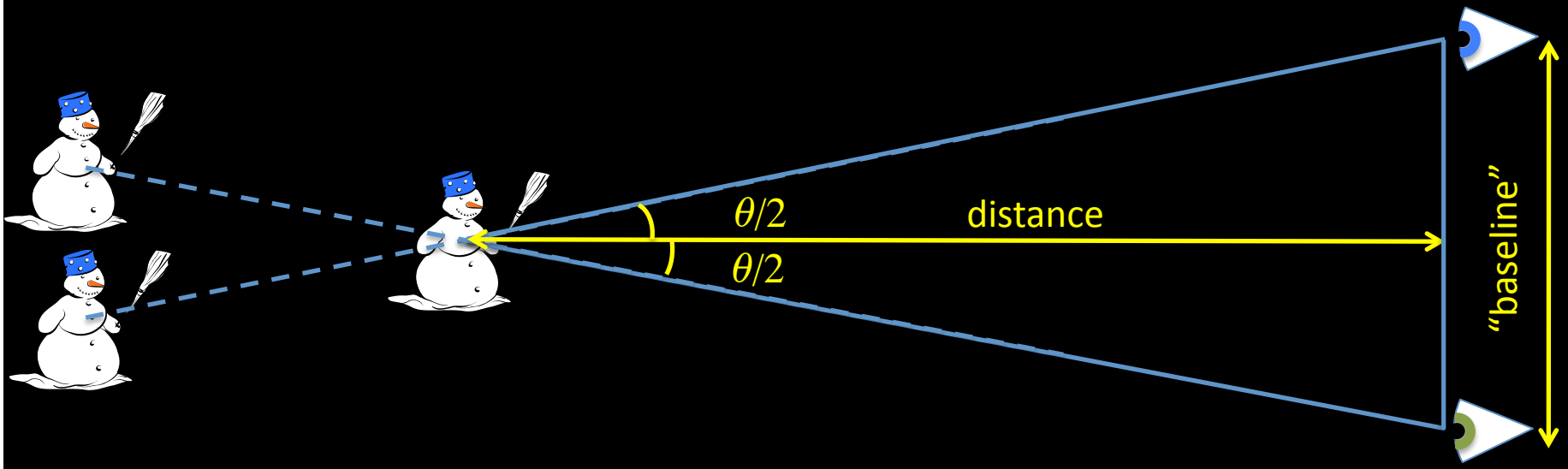


$$\tan(\theta) = \frac{"opposite"}{"adjacent"} = \frac{baseline}{distance}$$

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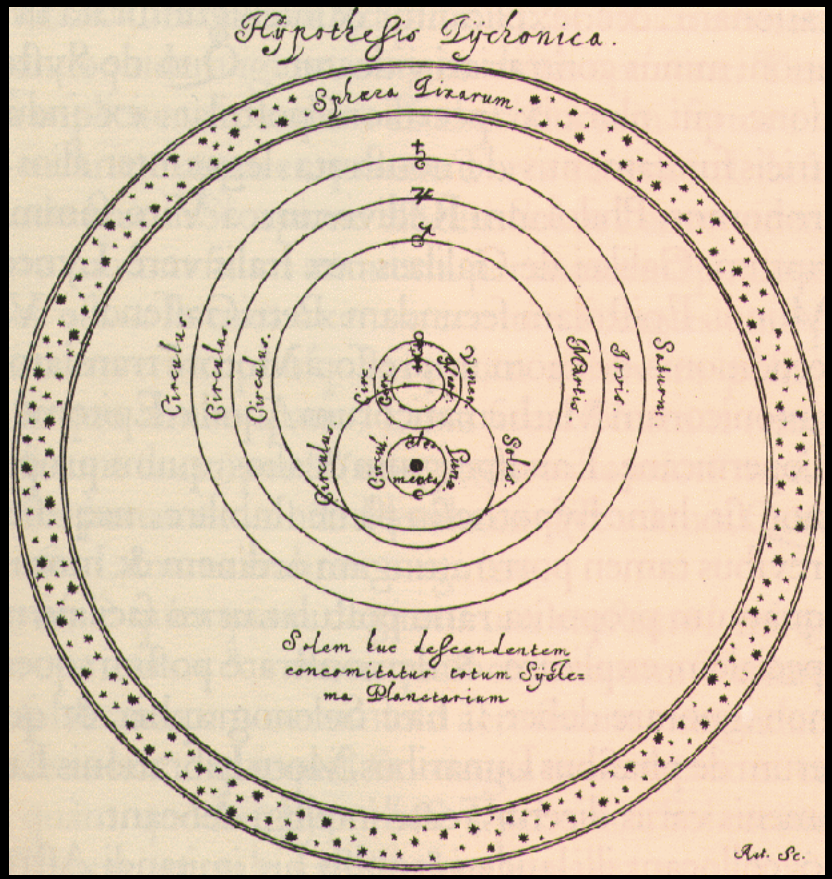


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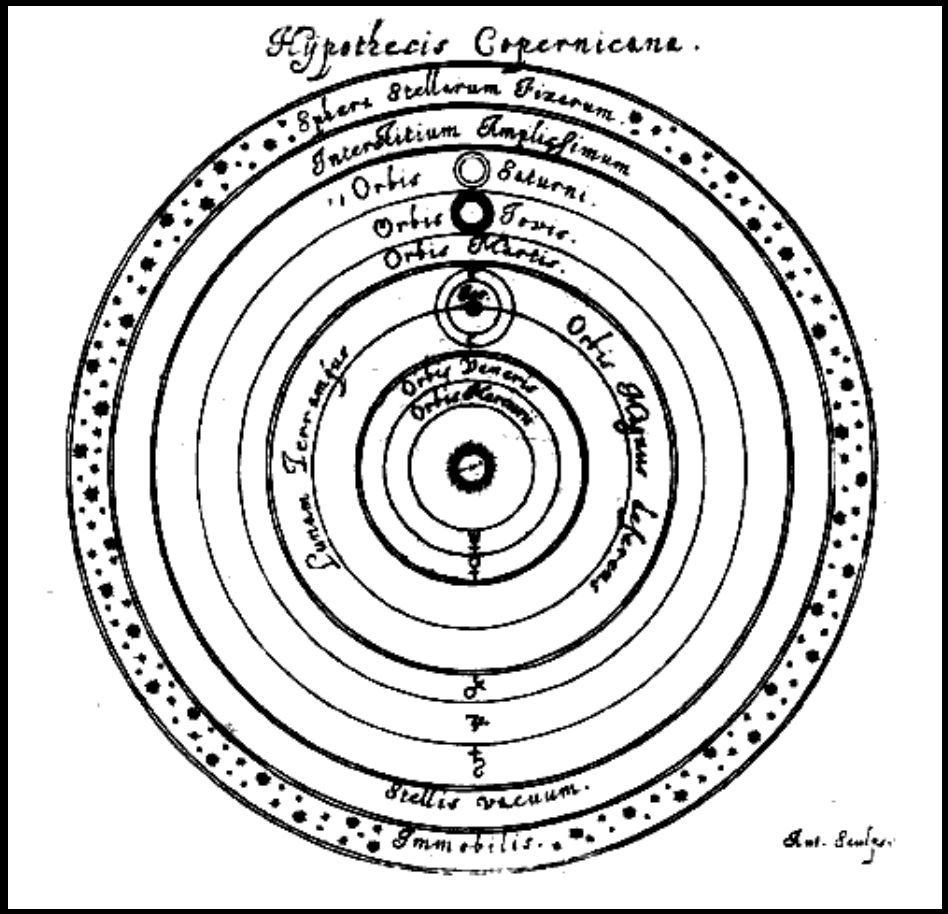


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- Since stellar parallax could not be observed, it was not possible to distinguish between these two models (at the time of Galileo).

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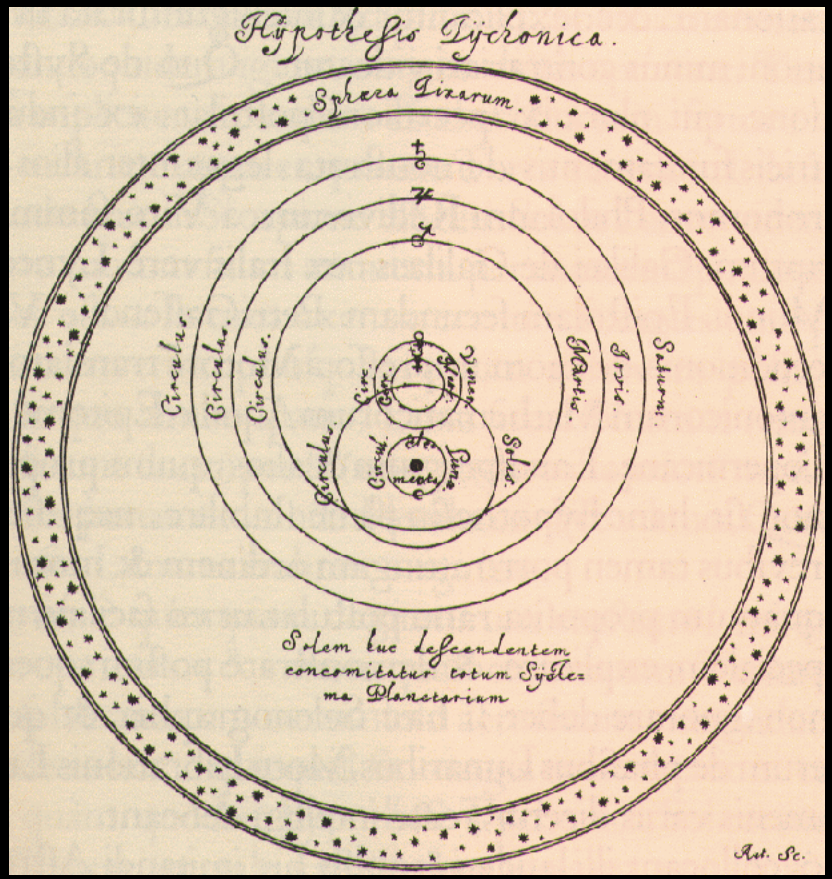


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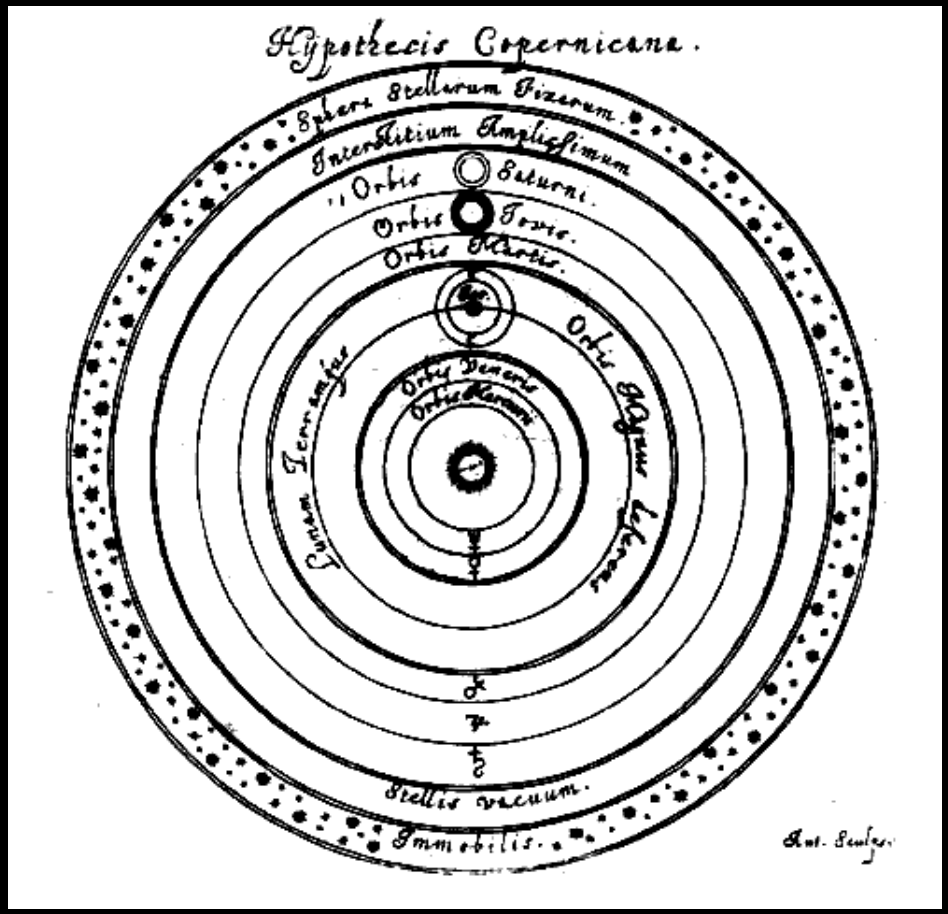


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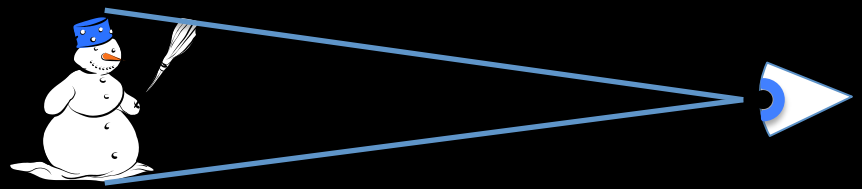
- Since stellar parallax could not be observed, it was not possible to distinguish between these two models (at the time of Galileo).
- Isaac Newton developed the laws of gravitation (published in 1687).
  - These indicated that the object with greater **mass** would be central.

# Parallax



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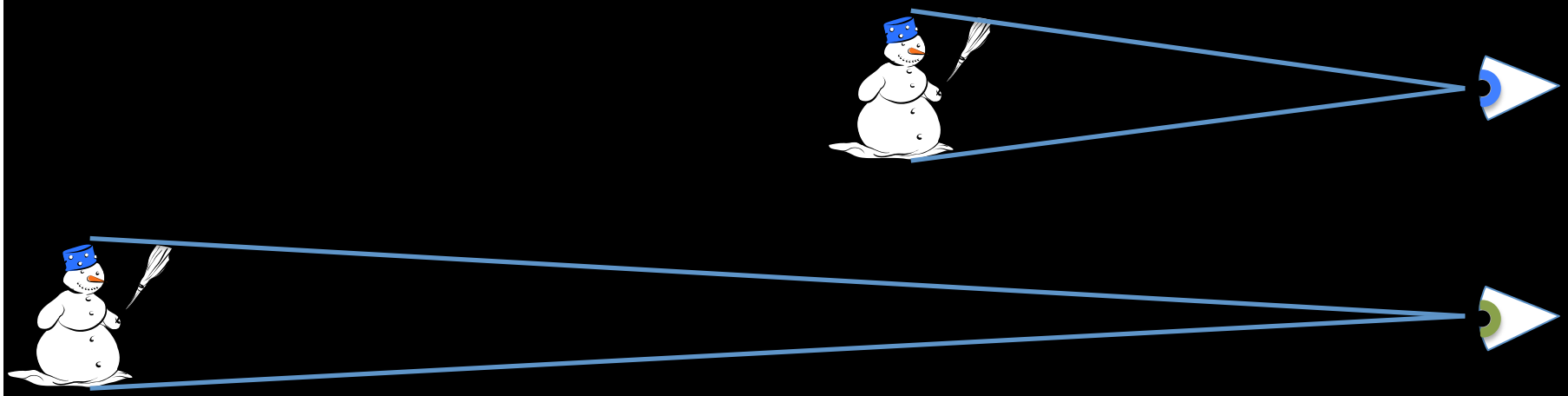

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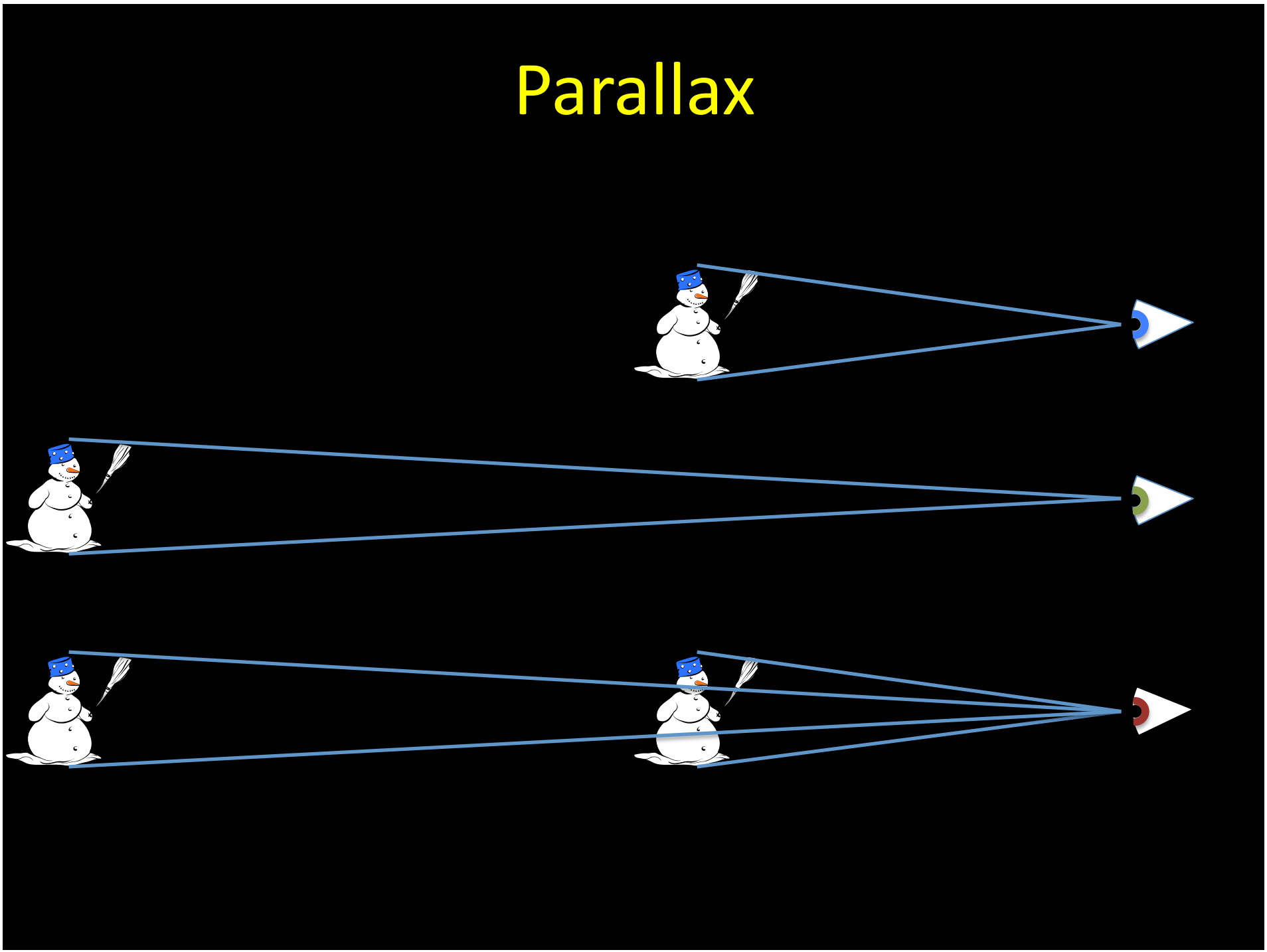

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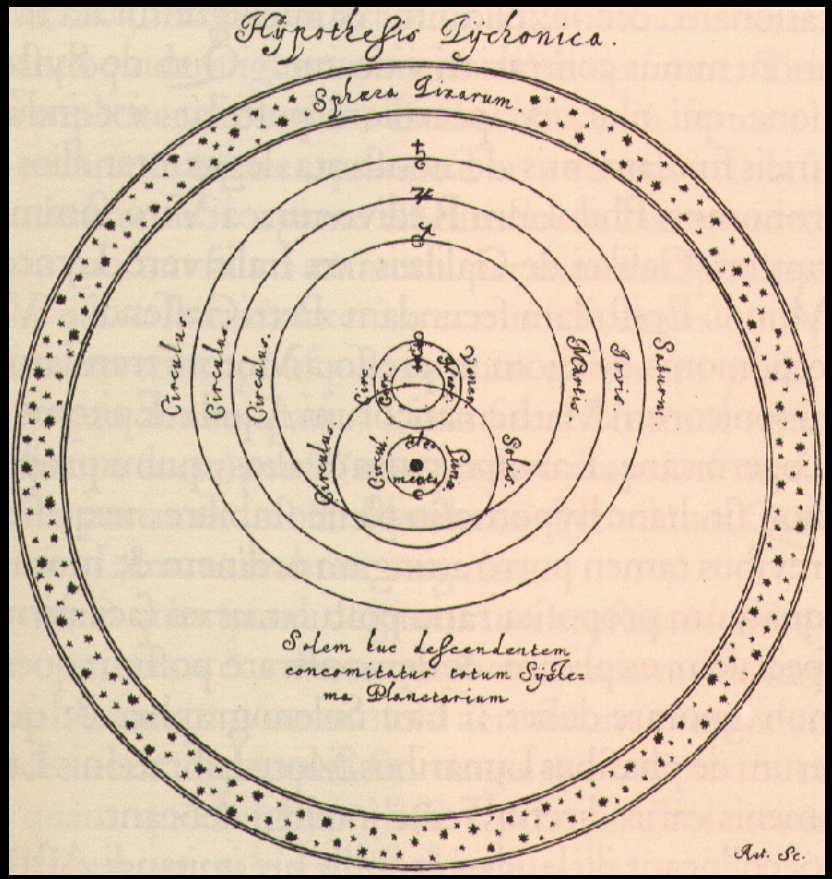


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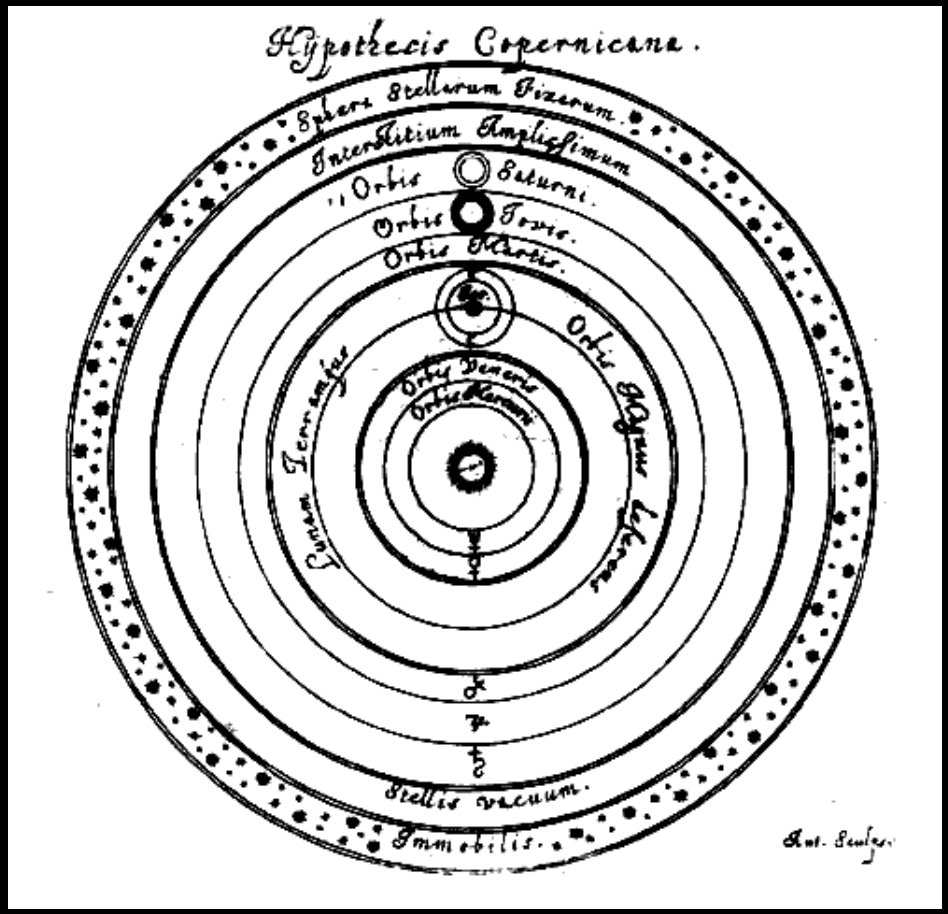


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- Isaac Newton developed the laws of gravitation (published in 1687).
  - These indicated that the object with greater **mass** would be central.
- But, nobody knew how far away the sun was, so its size was unknown…

# How to determine the mass of the Sun

Newton's Law of Gravitation:

$$F = \frac{Gm_1m_2}{r^2}$$

Newton's 2nd Law (on Earth)

$$\frac{GM_\oplus m_{object}}{R_\oplus^2} = m_{object}g$$

$$G = \frac{gR_\oplus^2}{M_\oplus}$$

Newton's 2nd Law:

$$F = ma$$

Replace G in Kepler's 3rd Law:

$$\frac{gR_\oplus^2}{M_\oplus} \cdot \frac{M_\Sigma}{4\pi^2} = \frac{d_\oplus^3}{P_\oplus^2}$$

Circular Acceleration:

$$a = \frac{v^2}{r} \qquad v = \frac{2\pi d_\oplus}{P_\oplus}$$

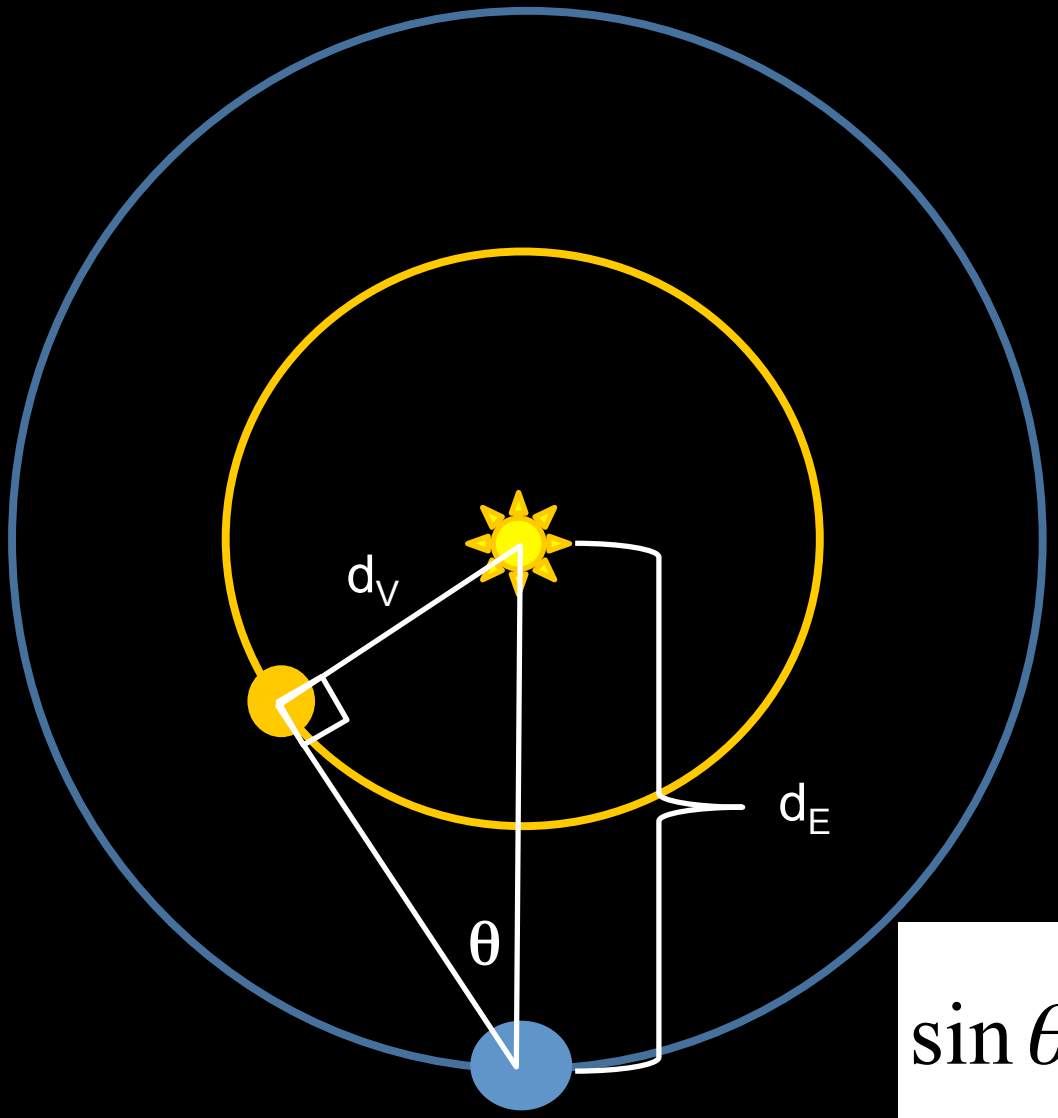
$$\frac{GM_\Sigma M_\oplus}{d_\oplus^2} = M_\oplus \frac{4\pi^2 d_\oplus}{P_\oplus^2}$$

Kepler's 3rd Law

$$\frac{GM_\Sigma}{4\pi^2} = \frac{d_\oplus^3}{P_\oplus^2}$$

$$\frac{M_\Sigma}{M_\oplus} = \frac{4\pi^2}{gR_\oplus^2} \cdot \frac{d_\oplus^3}{P_\oplus^2}$$

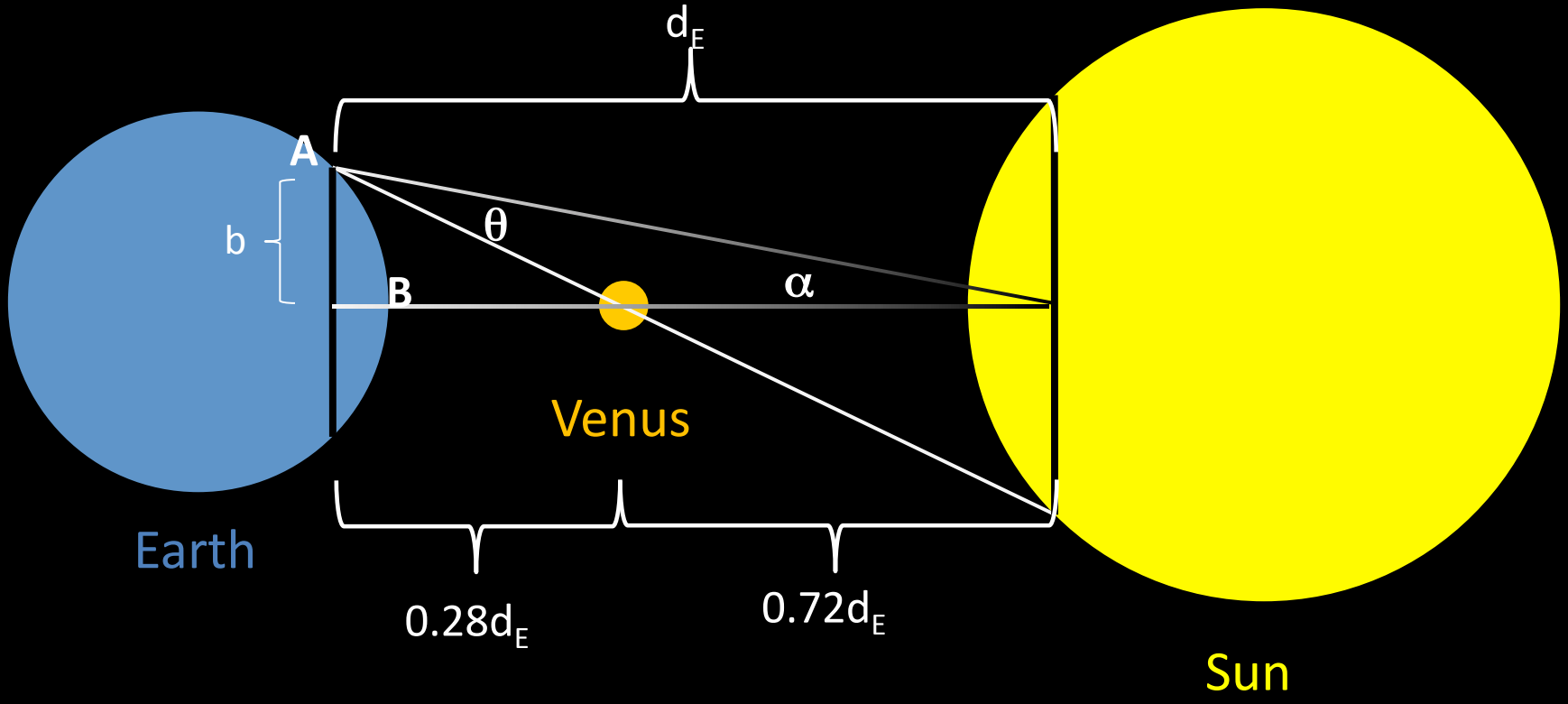
| $D_{sun}$ | $M_{sun}/M_{earth}$ |
|---|---|
| 300 $R_{earth}$ | 0.7 |
| 1,000 $R_{earth}$ | 26 |
| 3,000 $R_{earth}$ | 700 |
| 10,000 $R_{earth}$ | 26,000 |




We can determine the distances to any planet, in terms of the Earth-Sun distance (the Astronomical Unit, or AU) by means of easy observations and simple trigonometry!

$$\sin\theta = \frac{d_V}{d_E}$$

# Use transit of Venus to Measure the AU




$$d_E = \frac{b}{\theta} \cdot \frac{0.72}{0.28}$$

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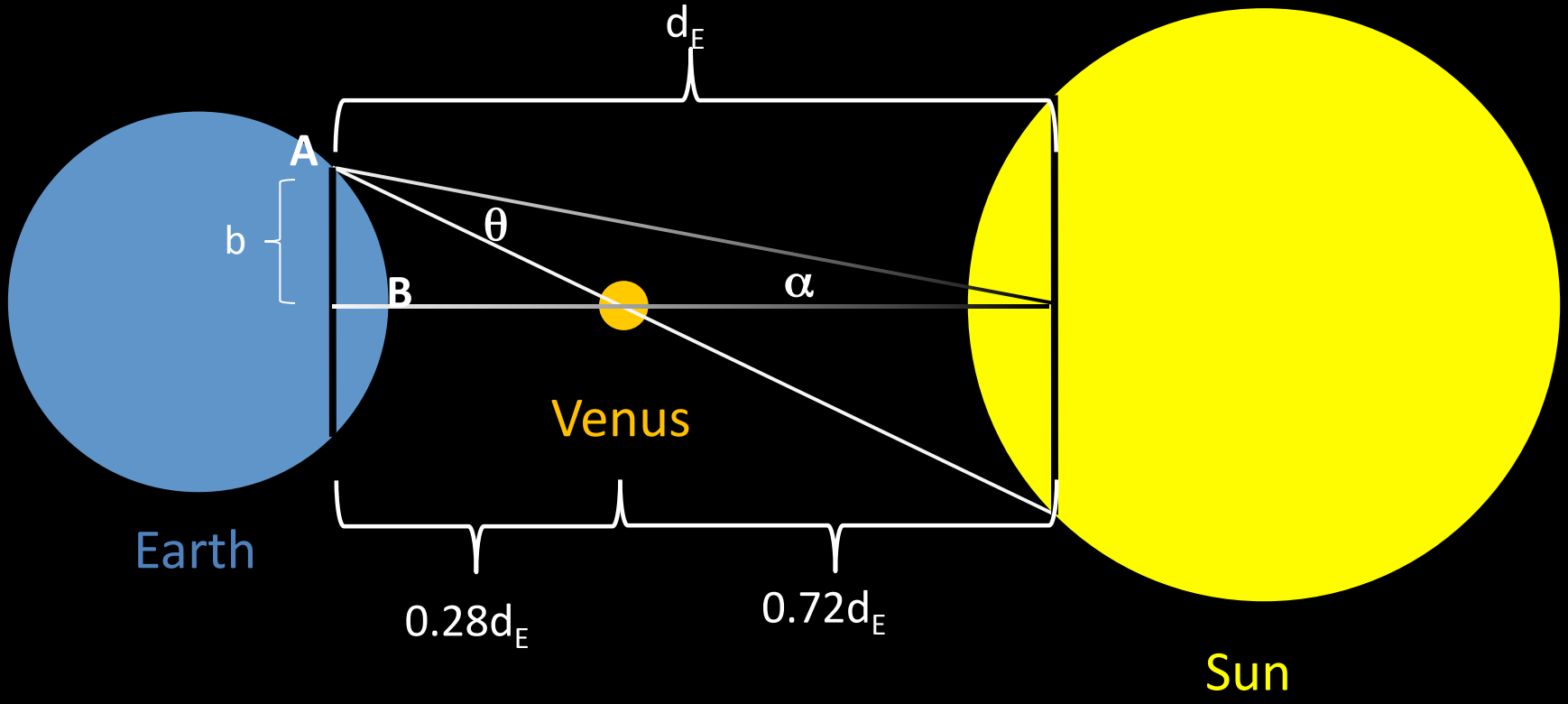
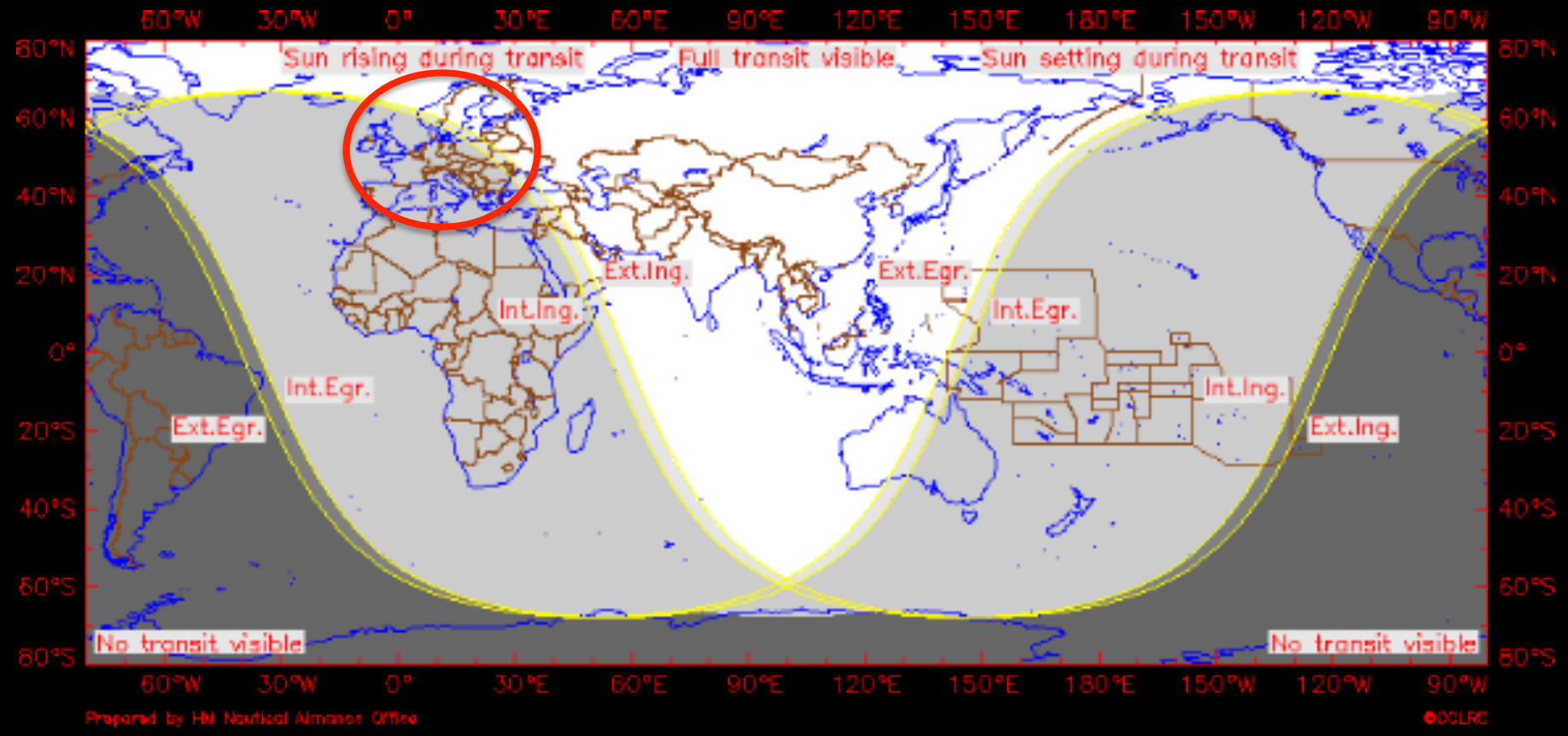




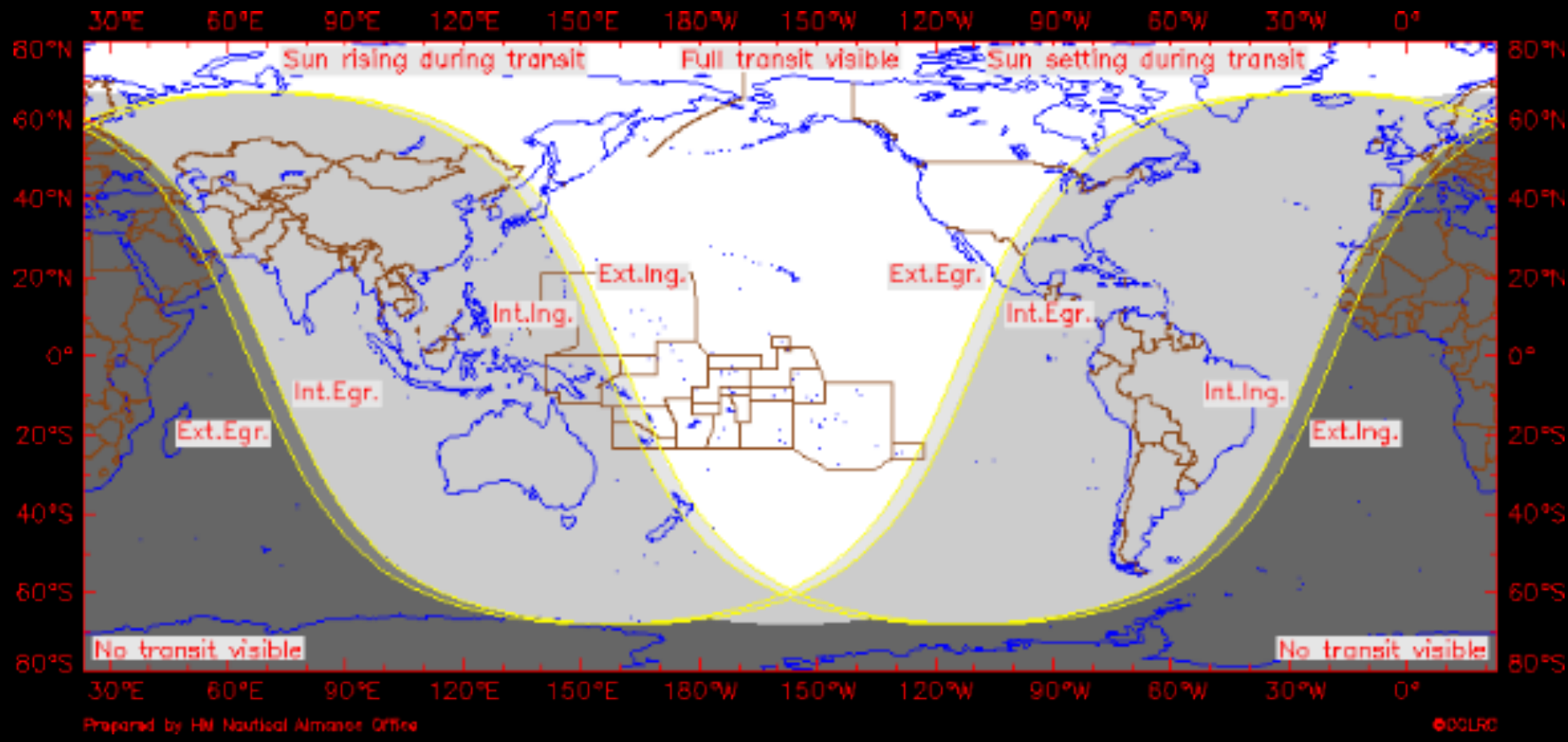
$$d_E = \frac{b}{\theta} \cdot \frac{0.72}{0.28}$$

# Venus Transit 1761



# Proof of a Venus atmosphere

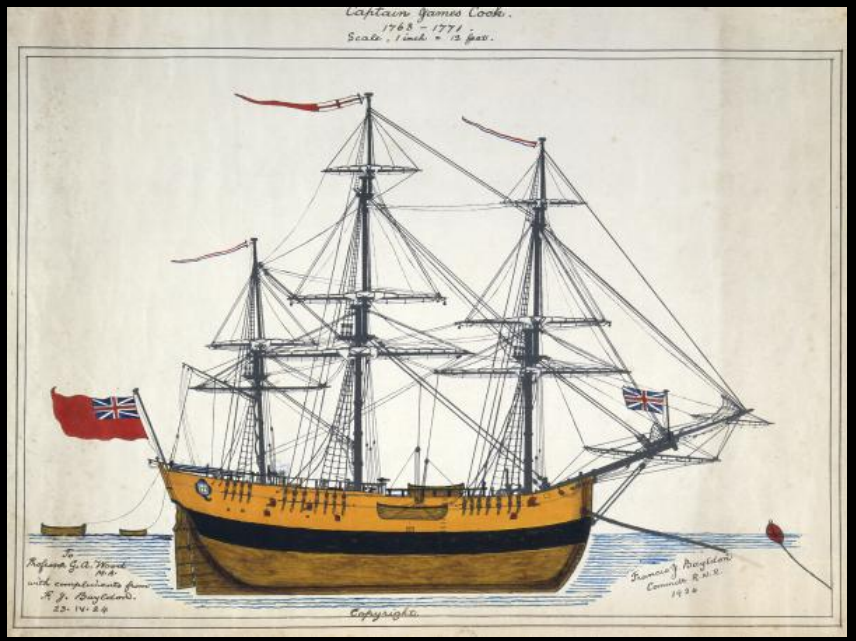

# Venus Transit 1769



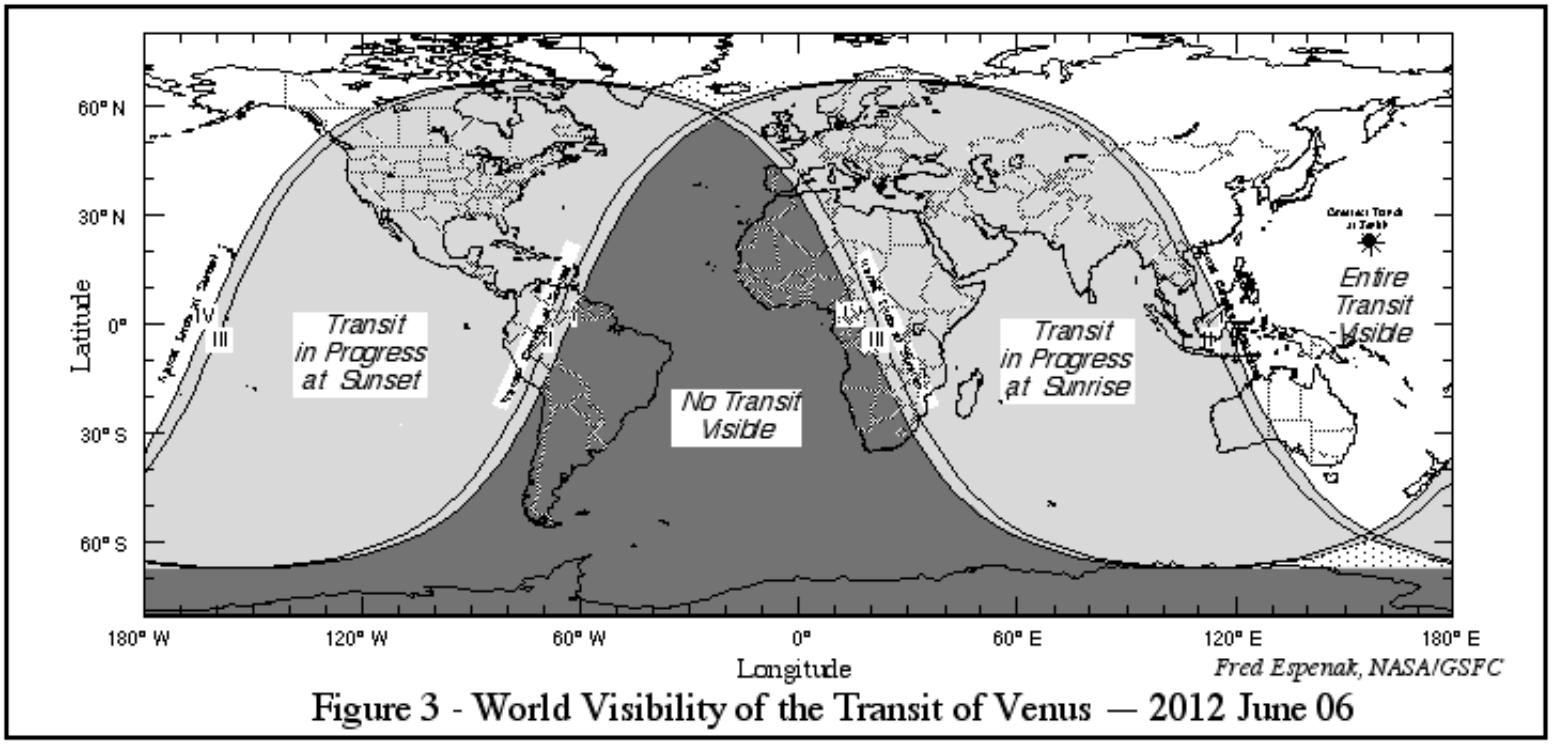

- Ships of several nations were dispatched on several-year missions for both scientific purposes and exploration of strange new lands, new civilizations, and uncharted frontiers. These were the voyages of …

# The USS Enterprise?

# Cap. Cook and HMS Endeavour



# Venus Transit 2012




Denver:

1st contact: 22:05:11 UTC (16:05:11 MDT), sun elevation: 47°

2nd contact: 22:22:47 UTC (16:22:47 MDT), sun elevation: 44°

center time of transit: 01:25:36 UTC, 6/6 (19:25:47 MDT), sun el: 9°

# Transit of Venus 2012

# The Venus Experience?

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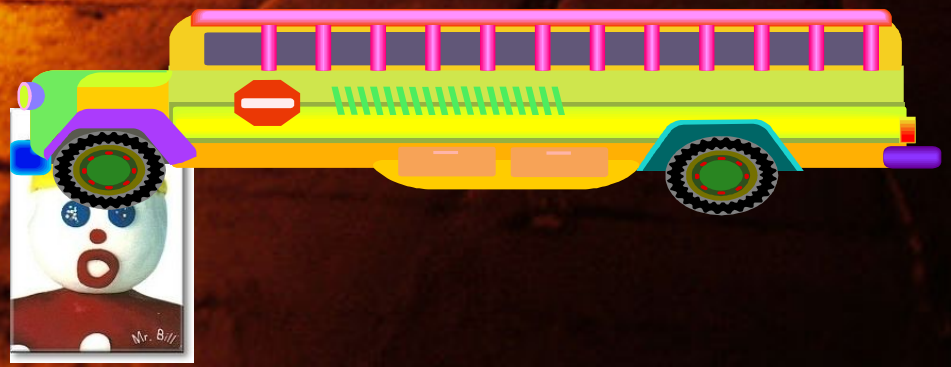
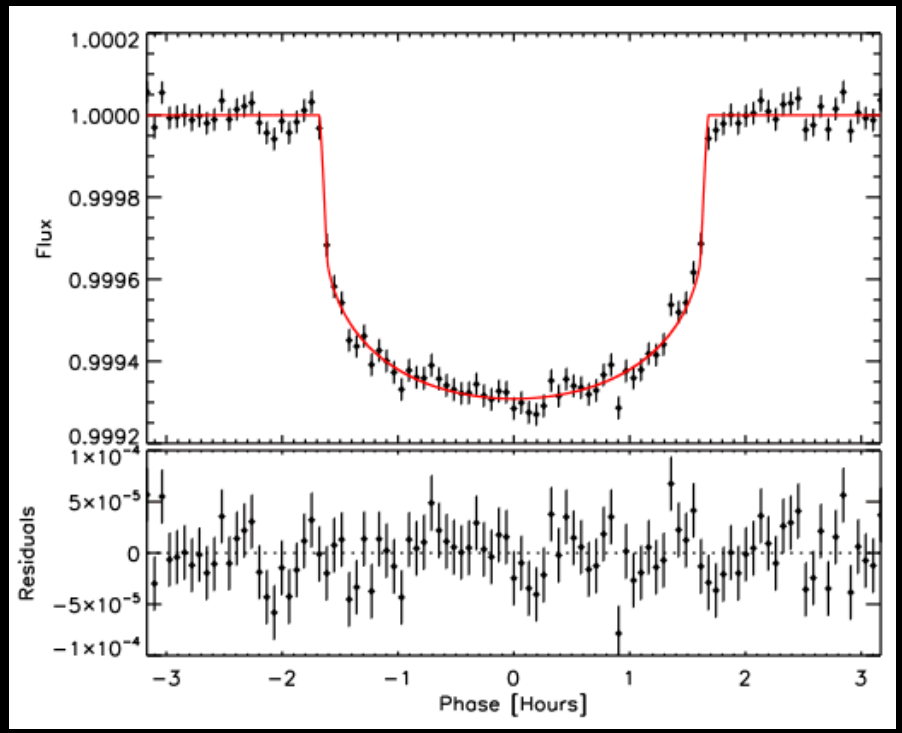
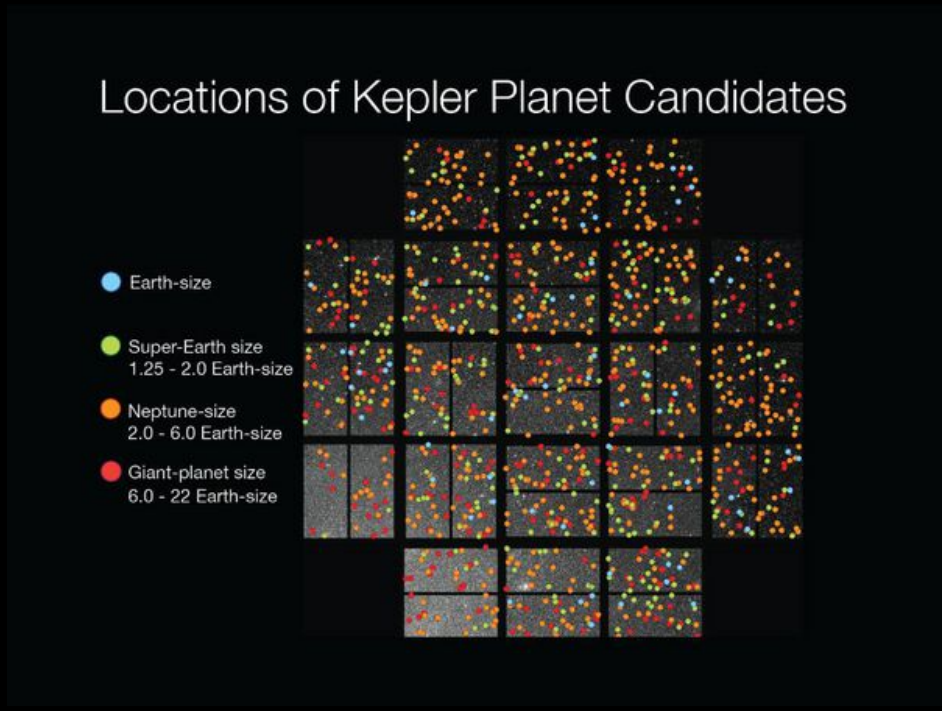


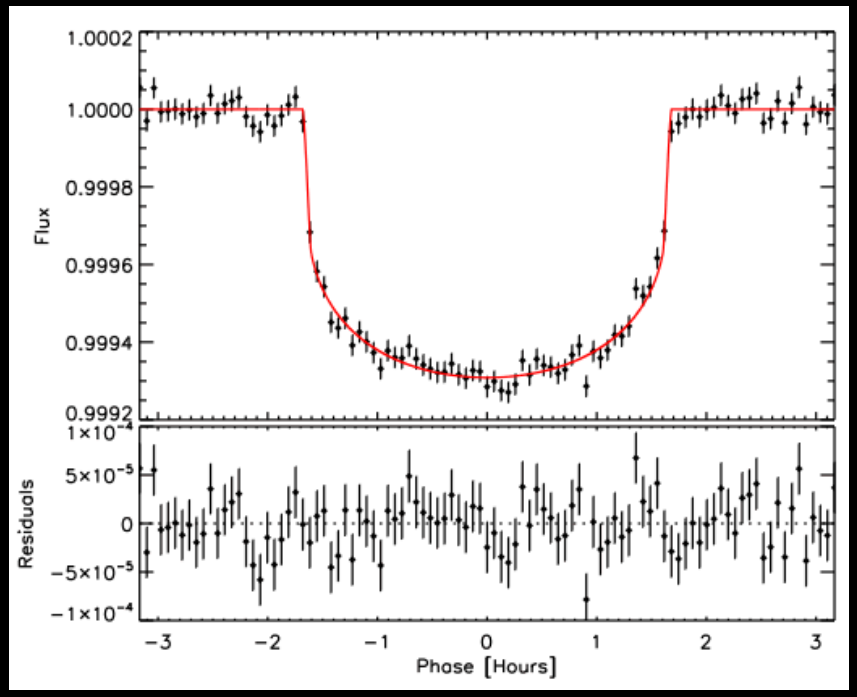

Image Courtesy J. Whatmore / ESA

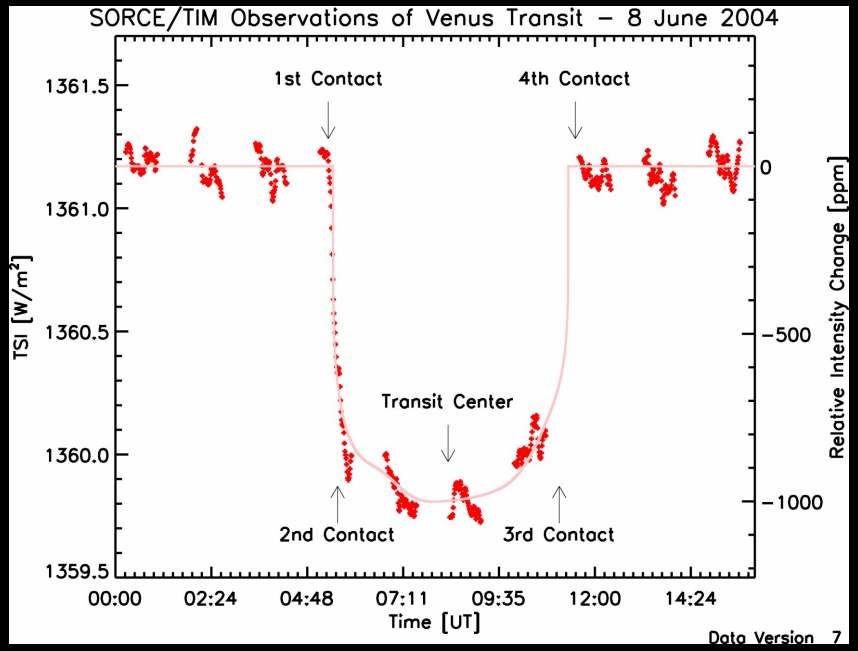
# Kepler Transiting Planets



# Observations of Venus Transit of 2004 with SORCE

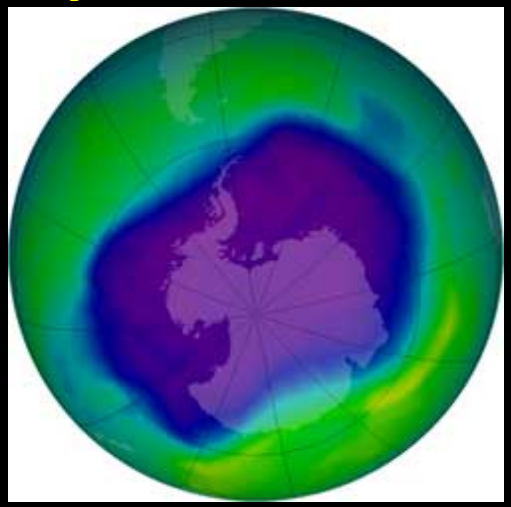


# Why Study Venus?
# Mariner 2 and Greenhouse Effect

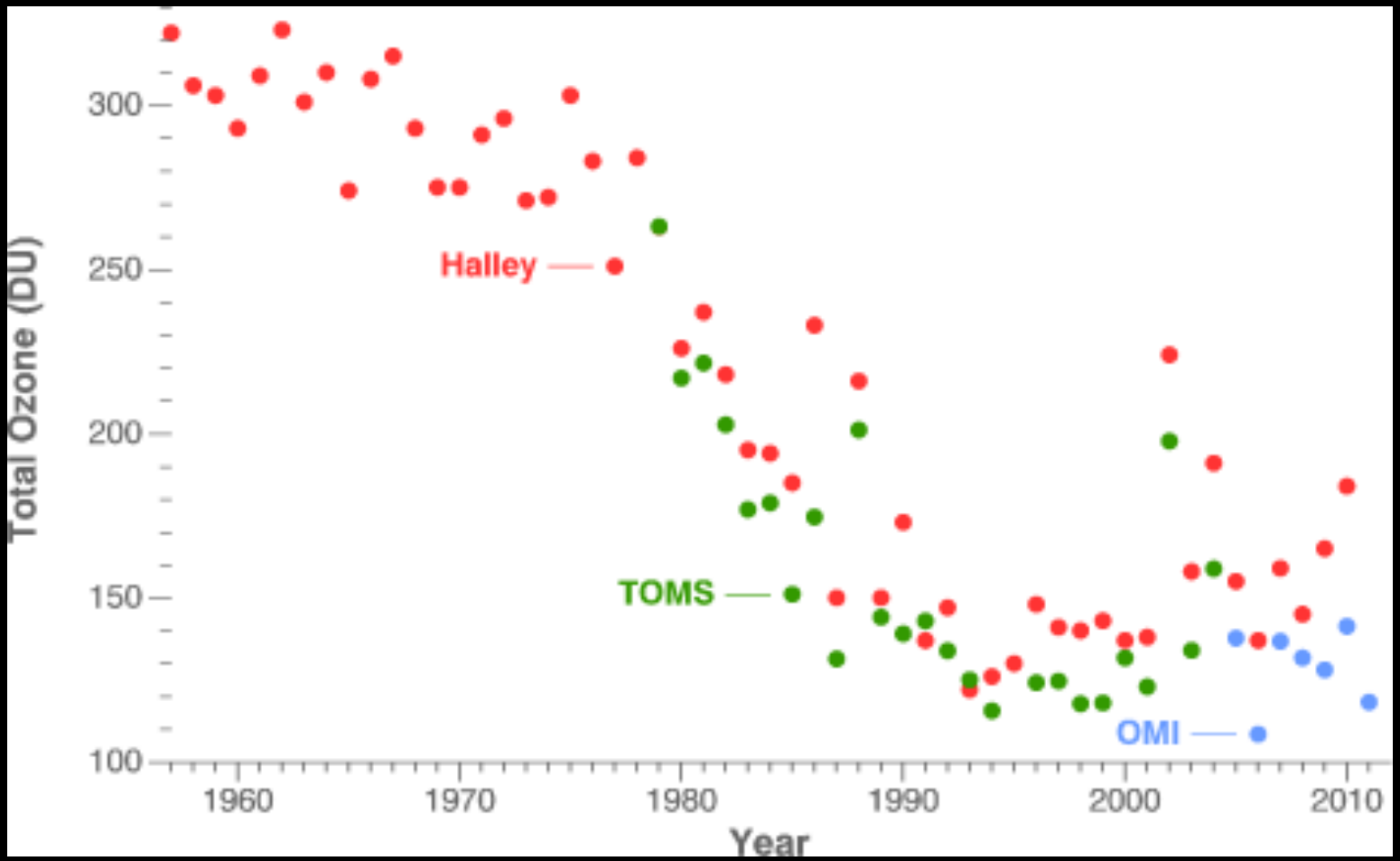
- Launched on 27 August 1962 (nearly 50 years ago), was the first successful scientific interplanetary probe from Earth.
- Confirmed VERY high surface temperature of Venus (T>600K).
- Sagan showed that this high surface temperature is a natural consequence of a strong $CO_2$ and $H_2O$ greenhouse effect.

# Why study Venus?
# Atmospheric Chemistry and Ozone

- In the 1970's and 80's, based on data from both Soviet and American missions to Venus, the photochemical reactions involving chlorine occurring in the Venus atmosphere were identified.
- In the 1970's it was realized that CFC's could reach the stratosphere, and had no sink other than photochemical destruction.
- In the mid 1980's, a depletion of ozone was detected over Antarctica.
- Since the photochemical models were already in place from Venus research, it was trivial to test them on Earth and find that free Chlorines from destruction of CFC's could destroy the ozone layer with alarming efficiency!

# Why study Venus?
# Atmospheric Chemistry and Ozone



# Why study Venus?
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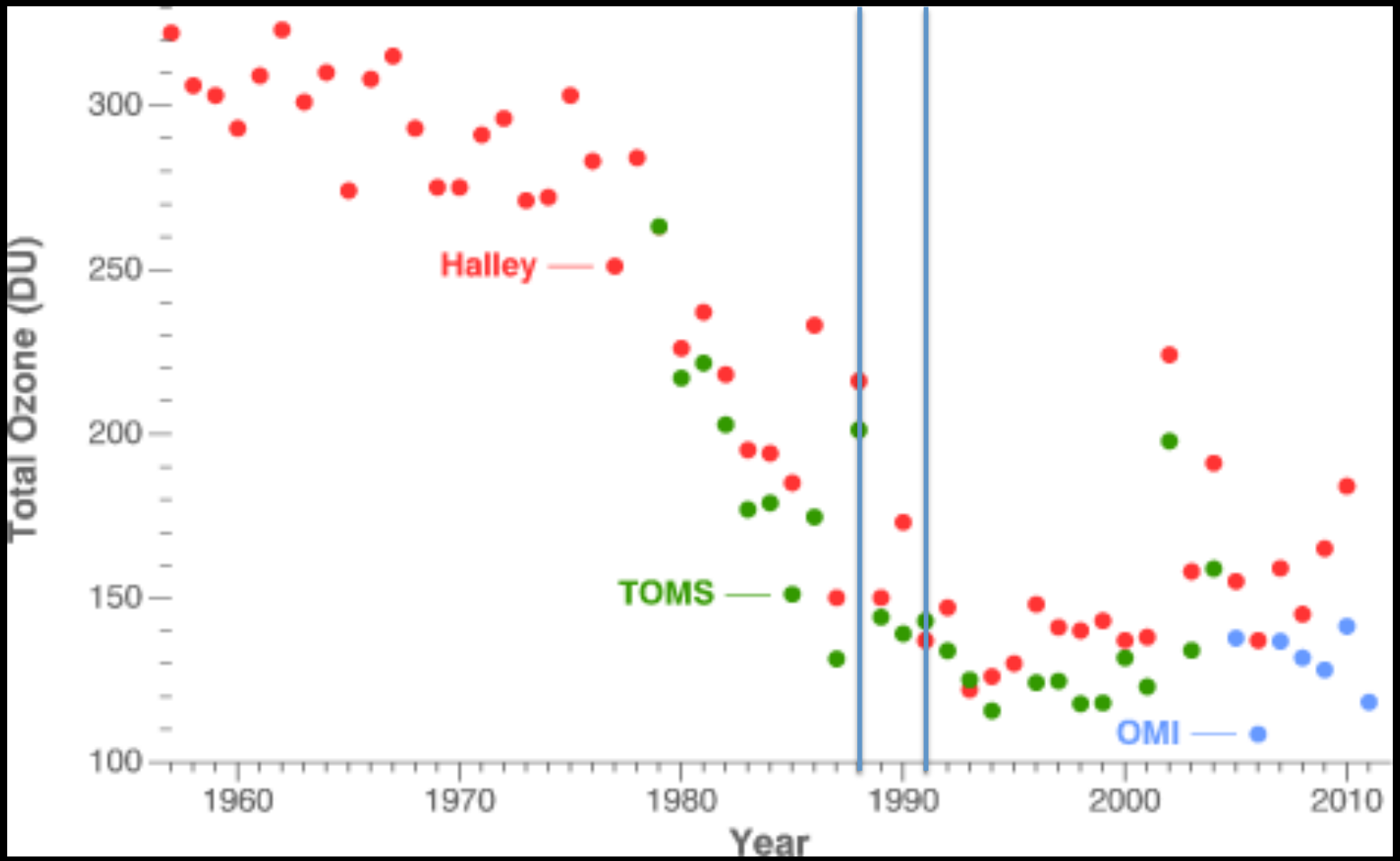
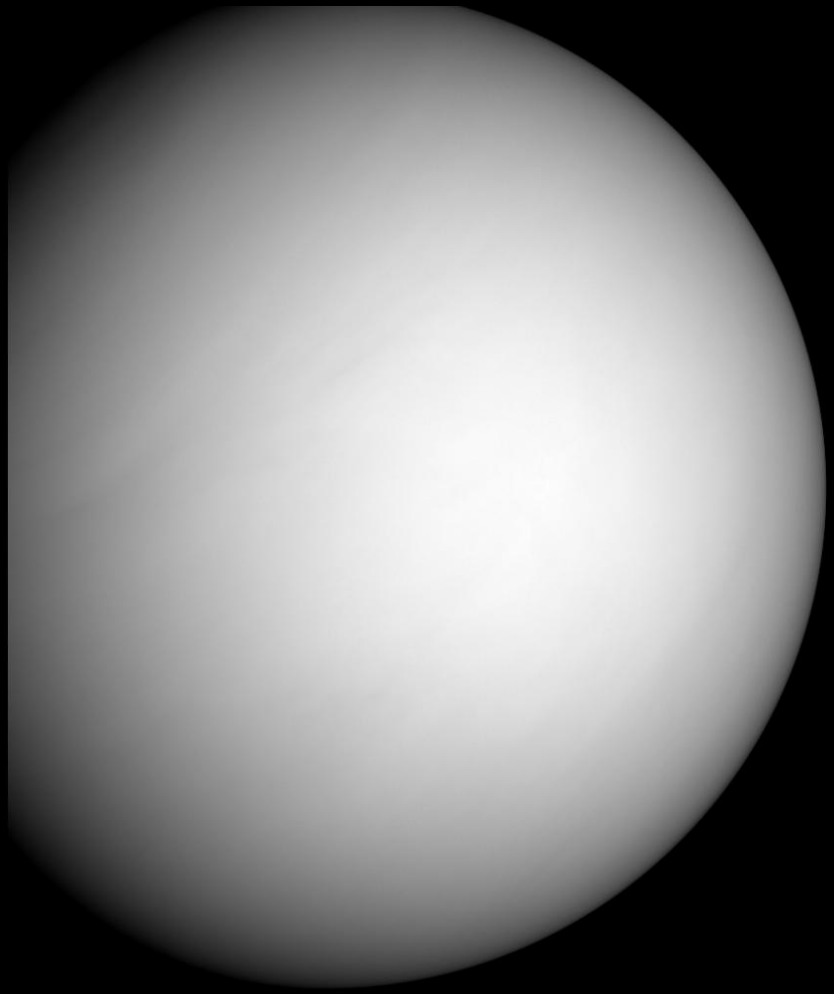


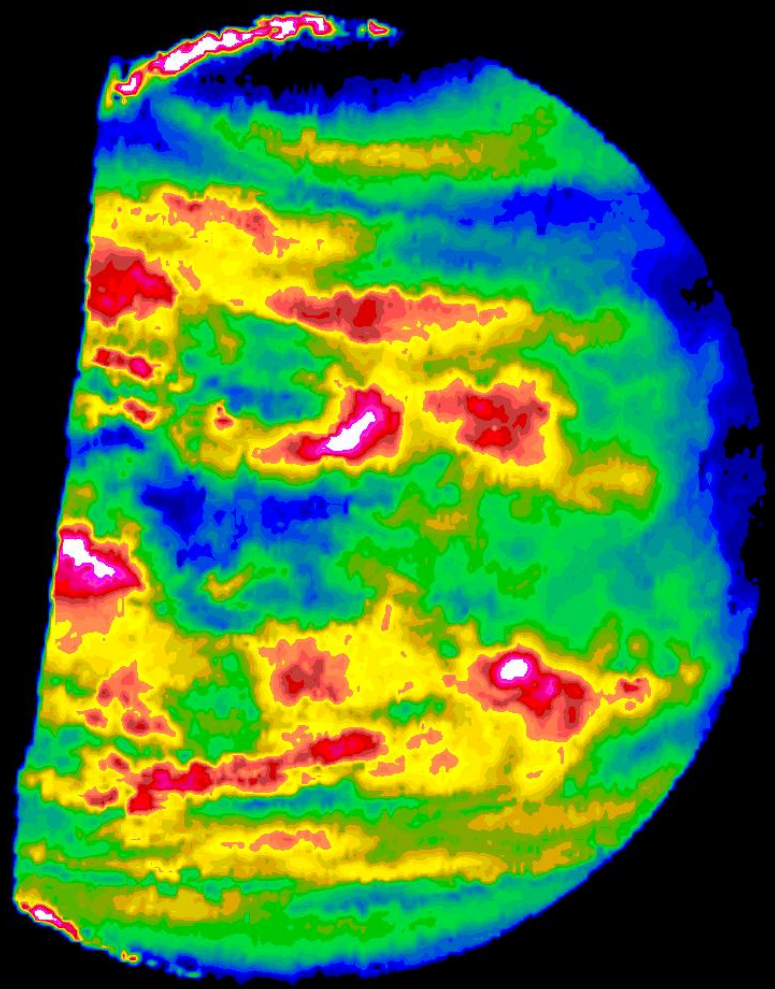

- In 1987, the Montreal Protocols were published, limiting the production of CFC's by all signatories (which include most of the developed world).
- By 1991, most nations had implemented mitigation measures

# Venus at Visible Wavelengths



NASA/Johns Hopkins University Applied Physics Laboratory/
Carnegie Institution of Washington (MESSENGER spacecraft)

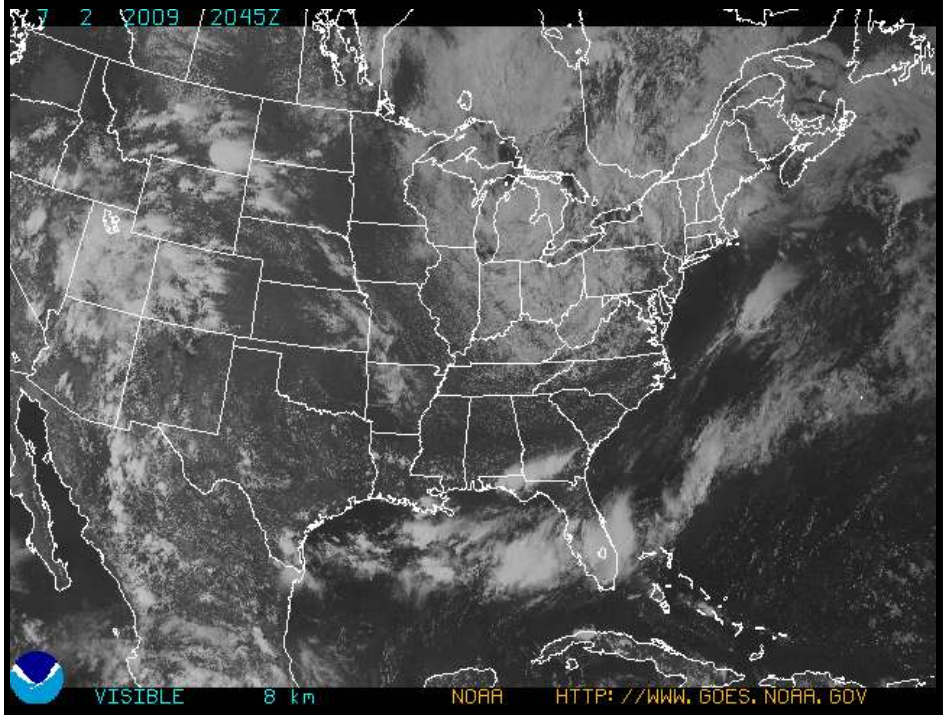
# Venus at Near Infrared Wavelength



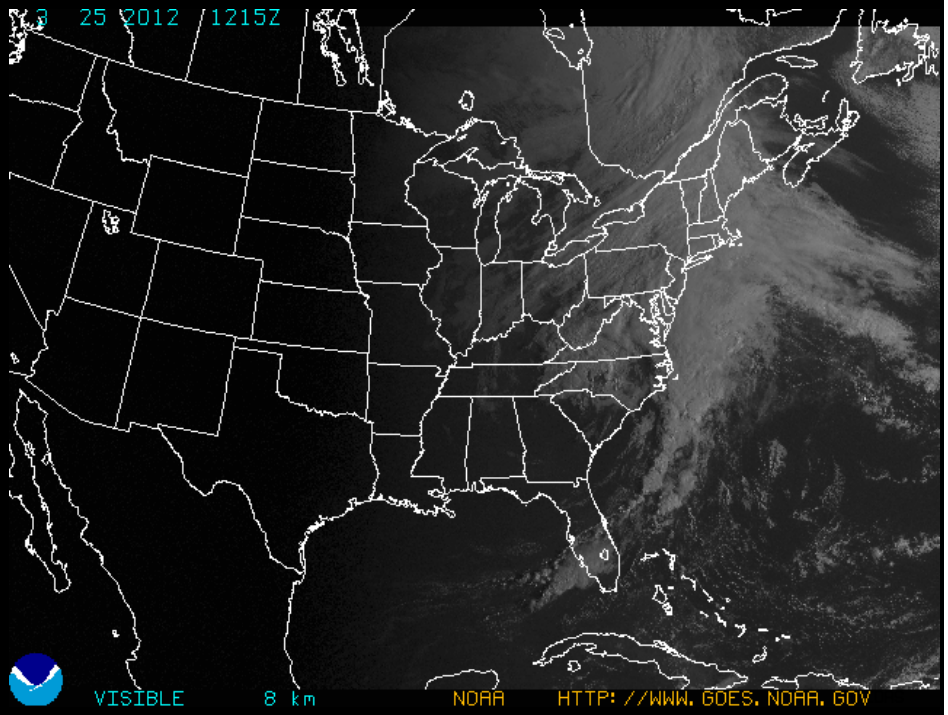
NASA/Jet Propulsion Laboratory (Galileo spacecraft)

# Earth at visible wavelengths

## Visible

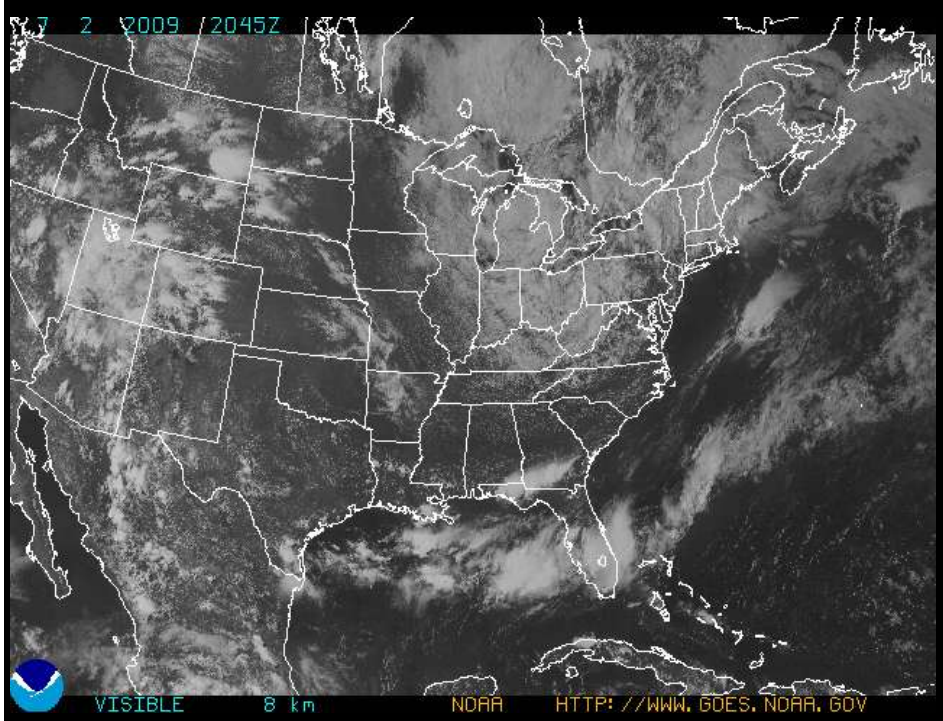



## Visible near eastern dawn

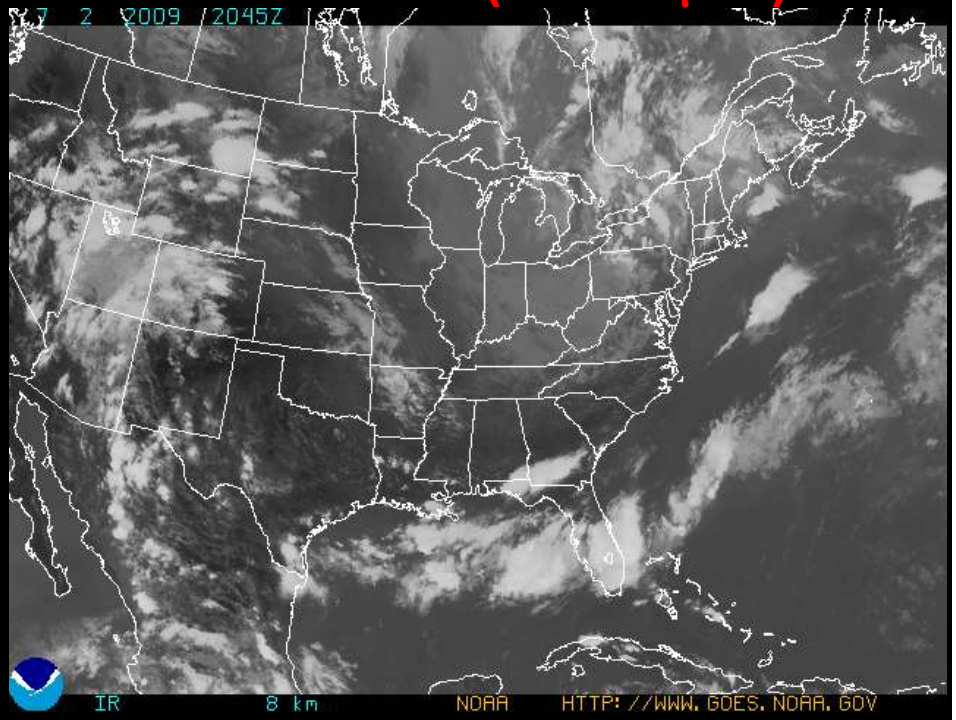


# Earth at visible wavelengths

**Visible**

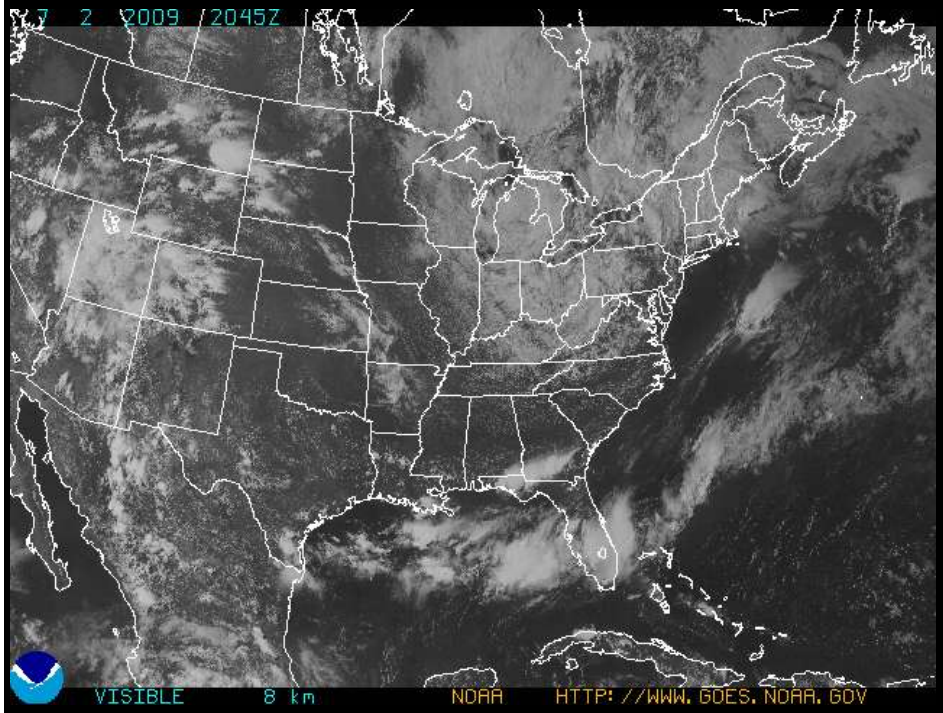


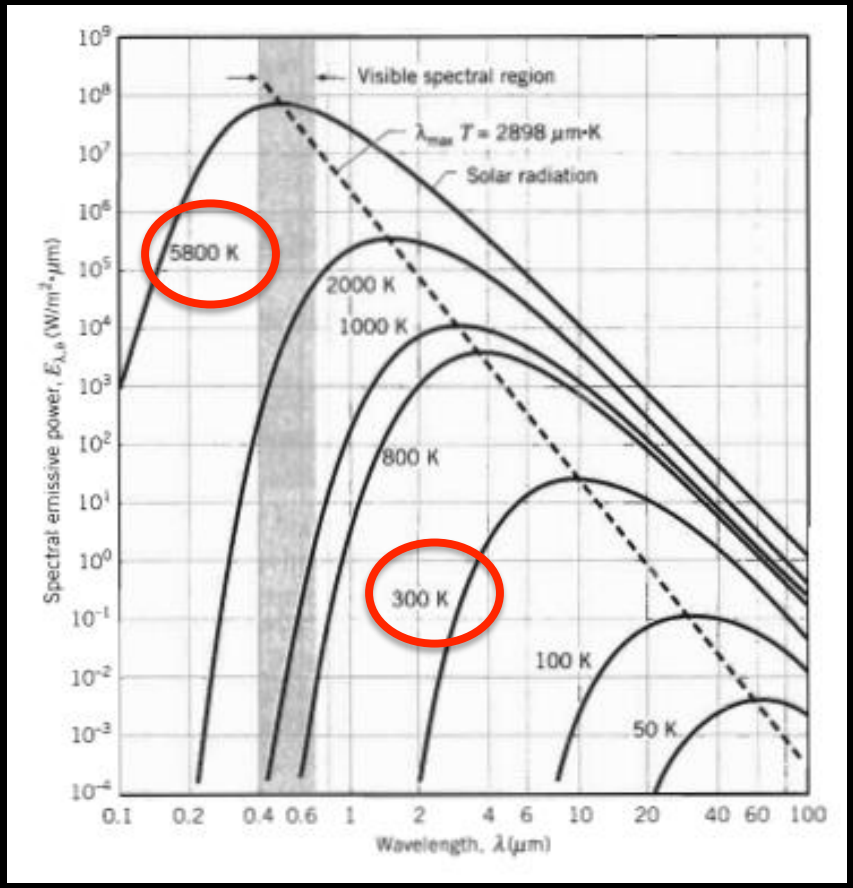

**Infrared (10.70 μm)**



# Earth at visible wavelengths

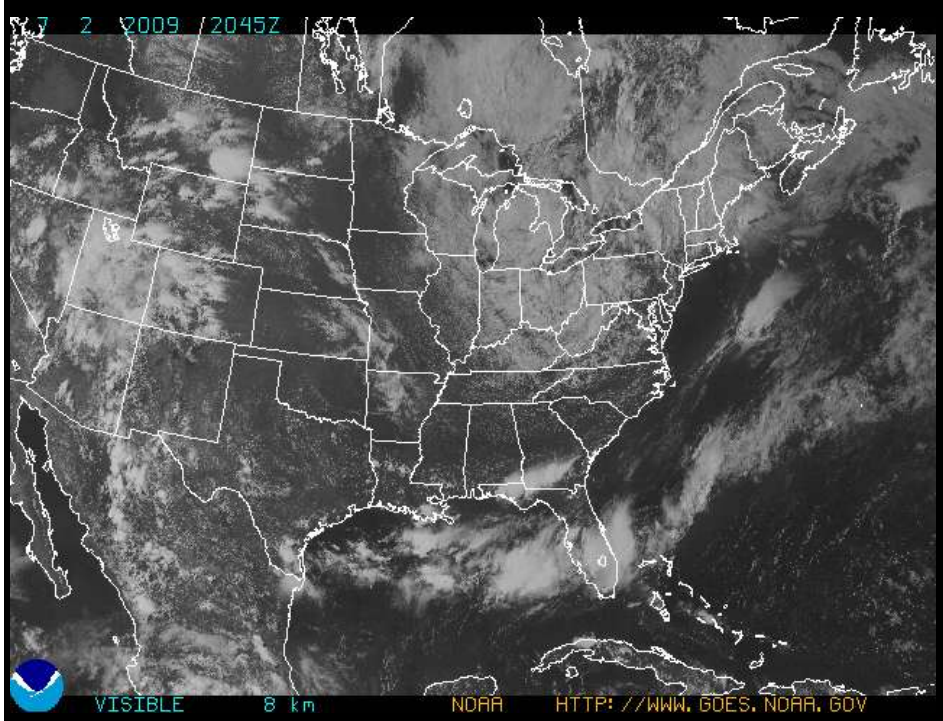
## Visible



# Earth at visible wavelengths

**Visible**

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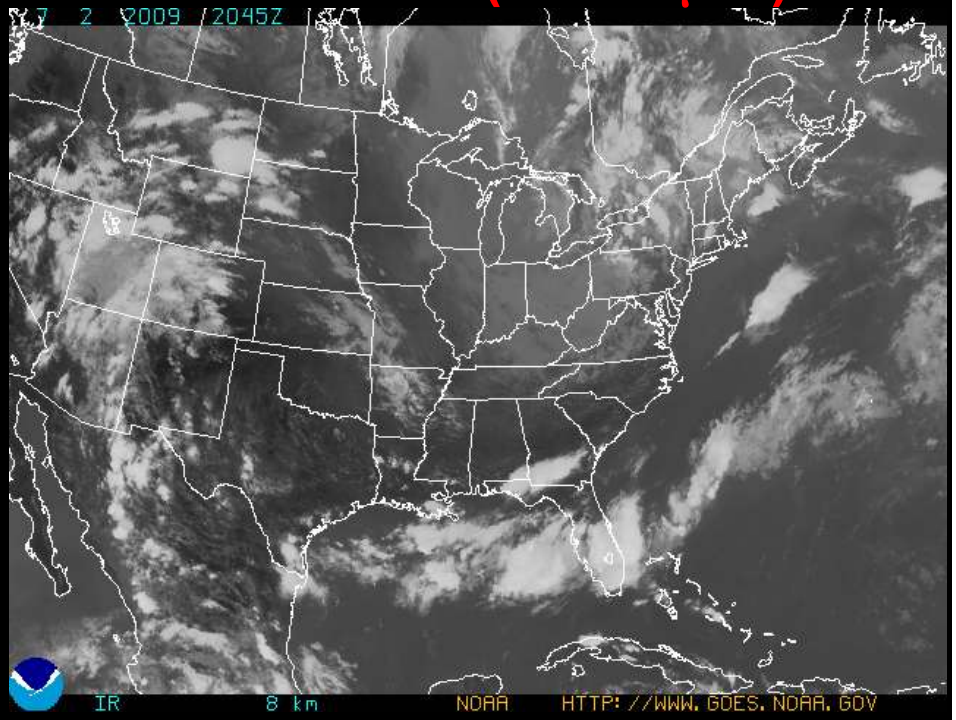
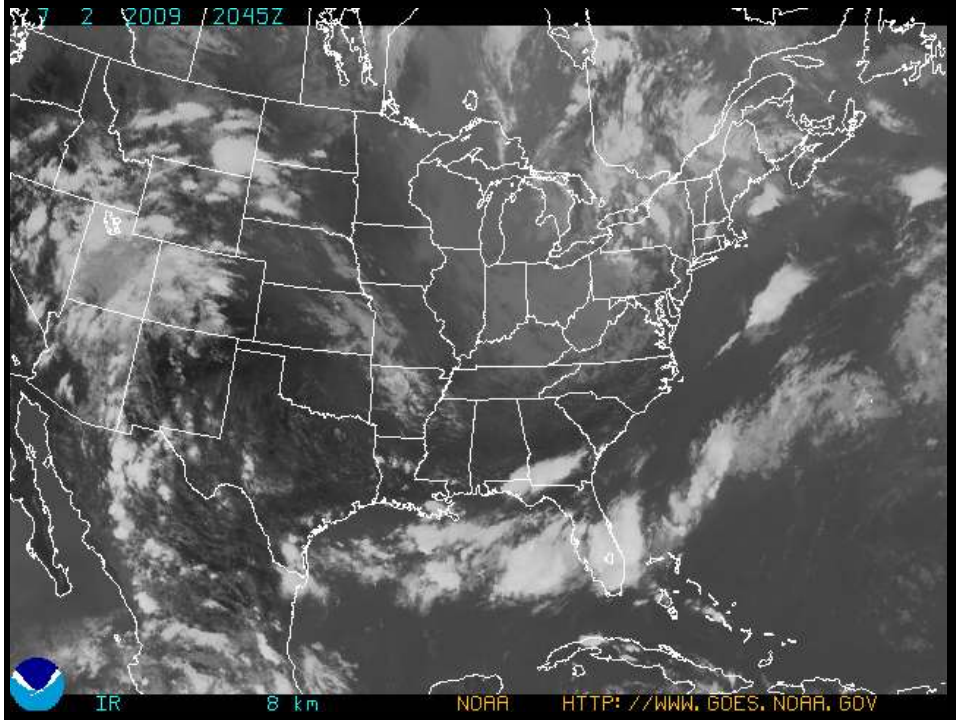
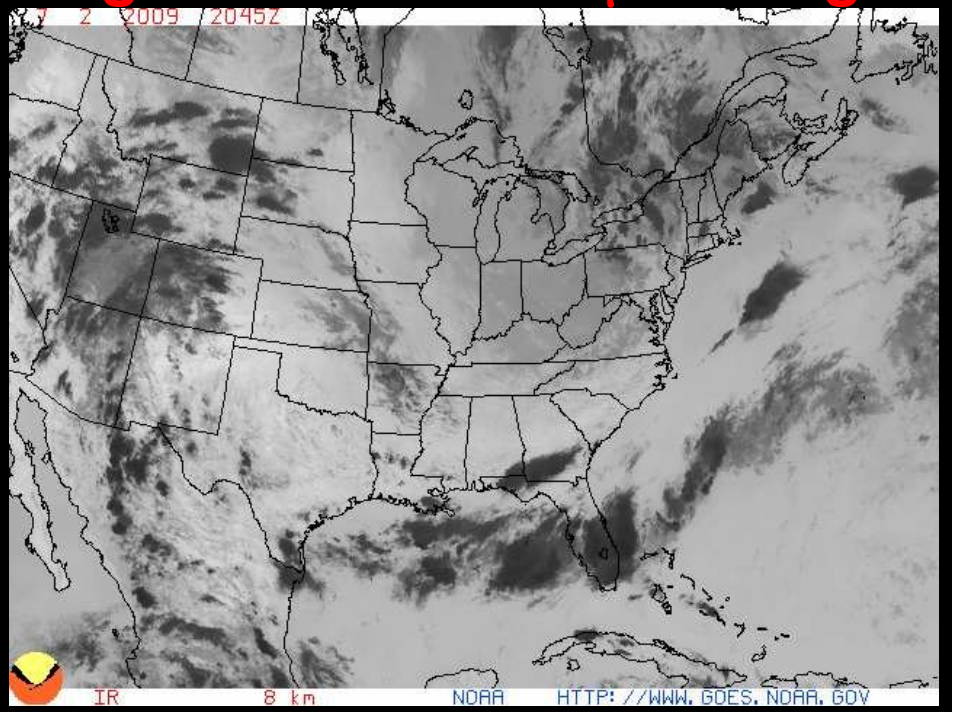


# “Raw” Infrared data

**10.70 μm**

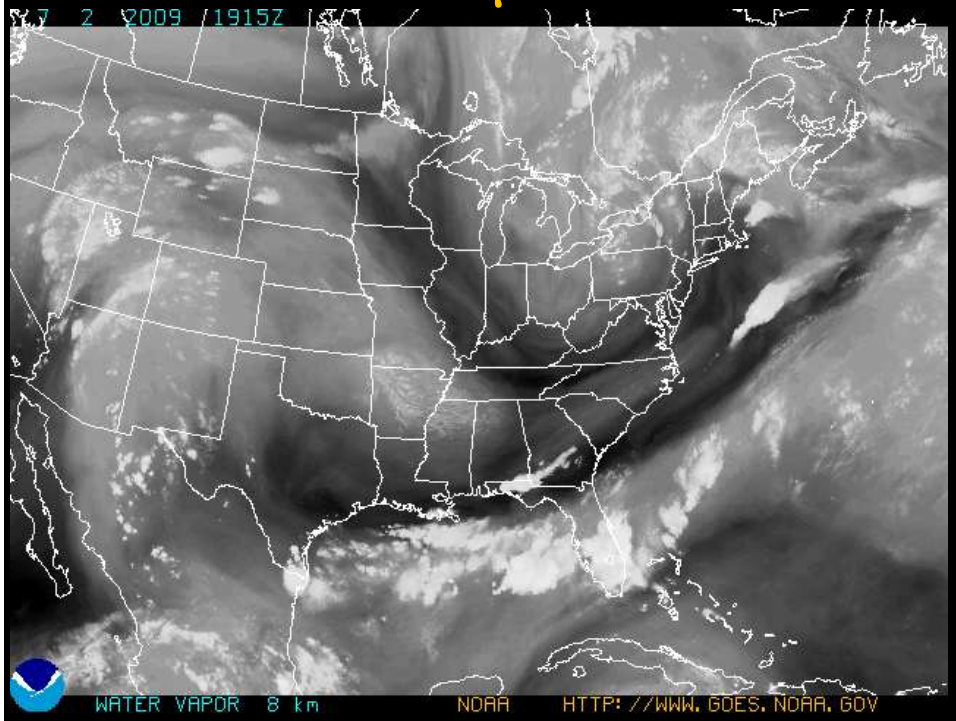



**“Negative” of 10.70 μm image**

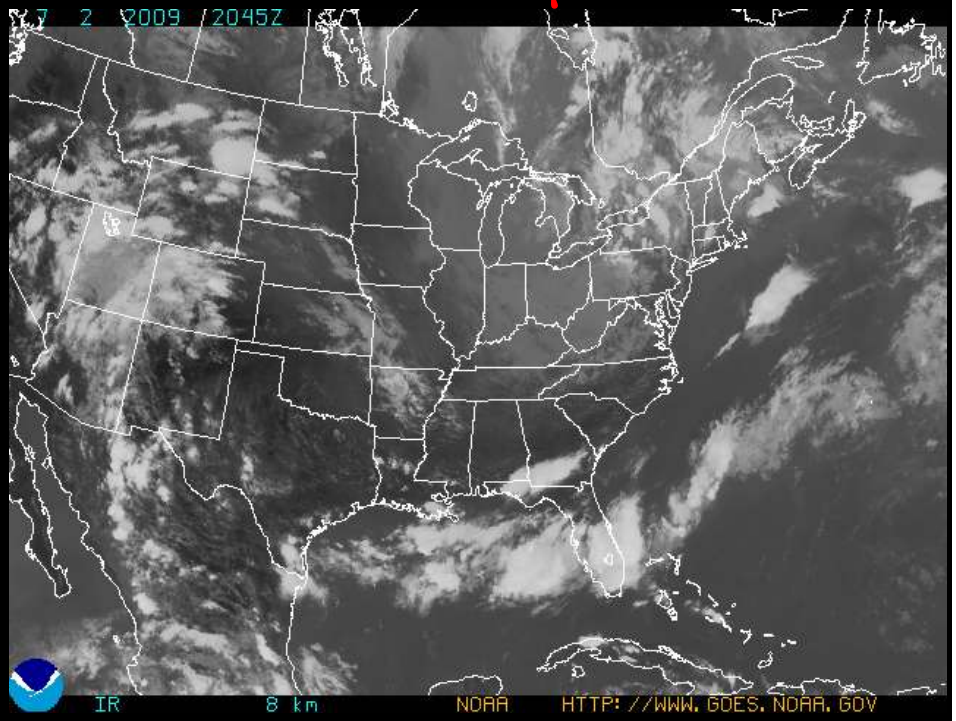


# IR at different wavelengths

**6.70 μm**

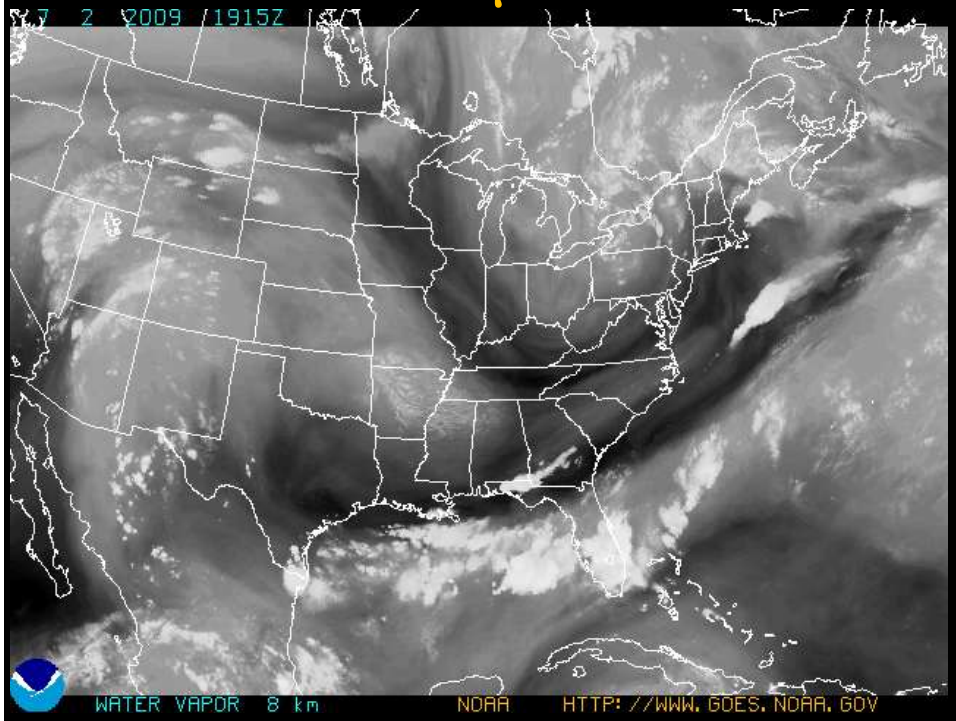



**10.70 μm**

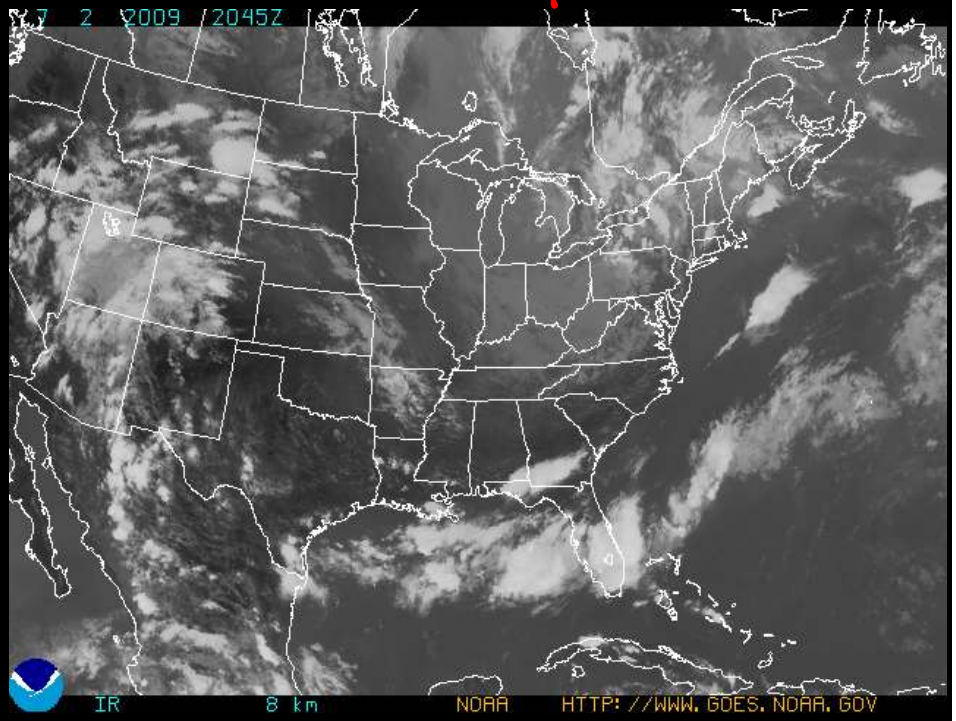


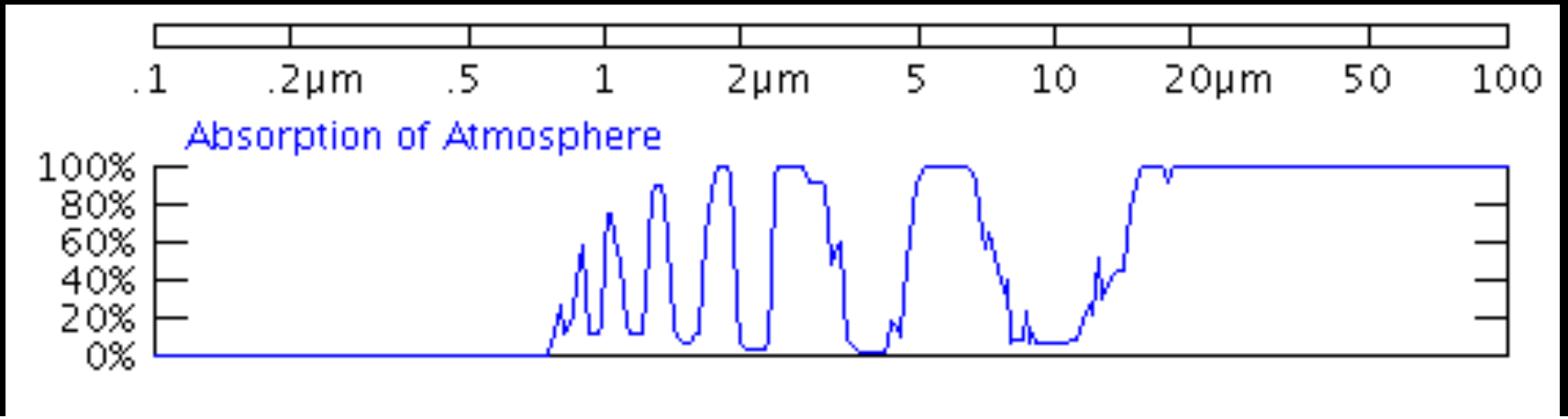
# IR at different wavelengths

**6.70 μm**

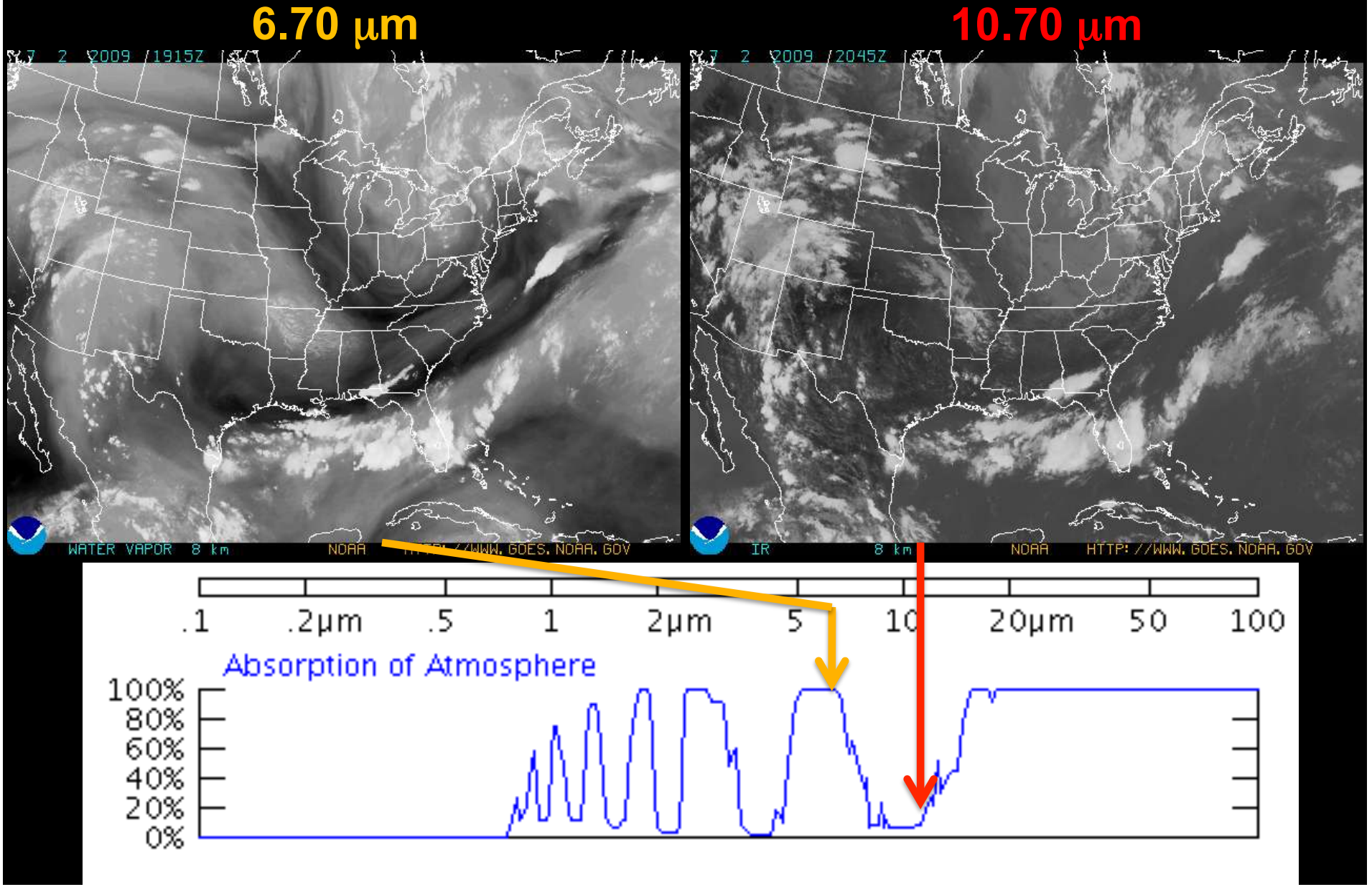



**10.70 μm**

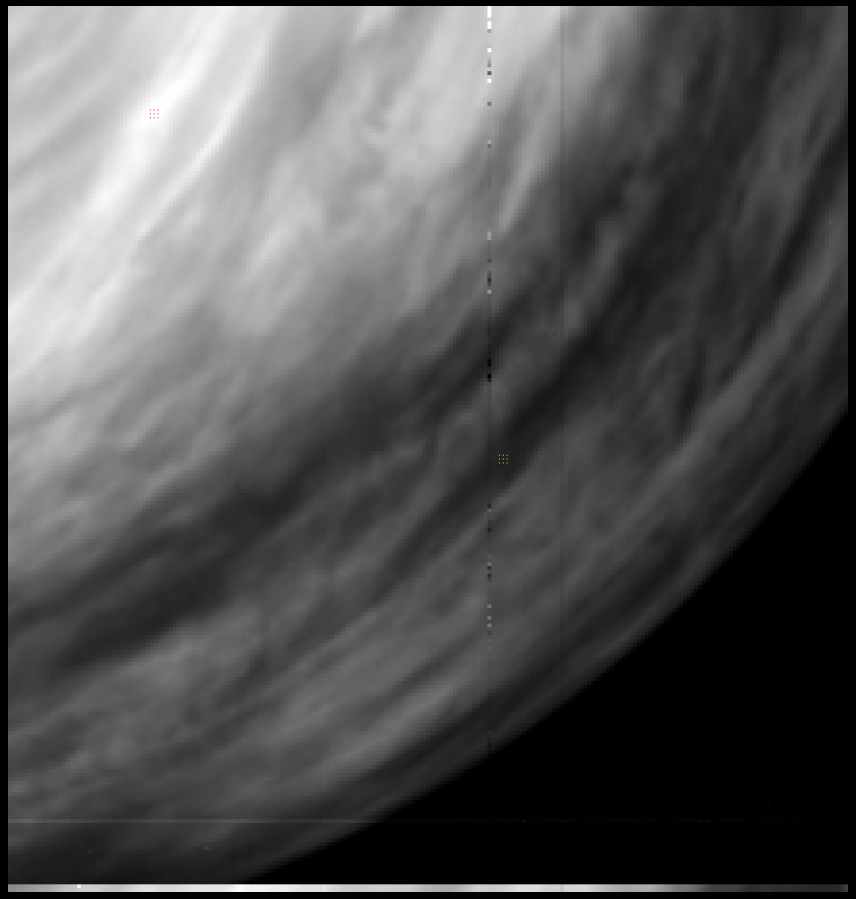


# IR at different wavelengths



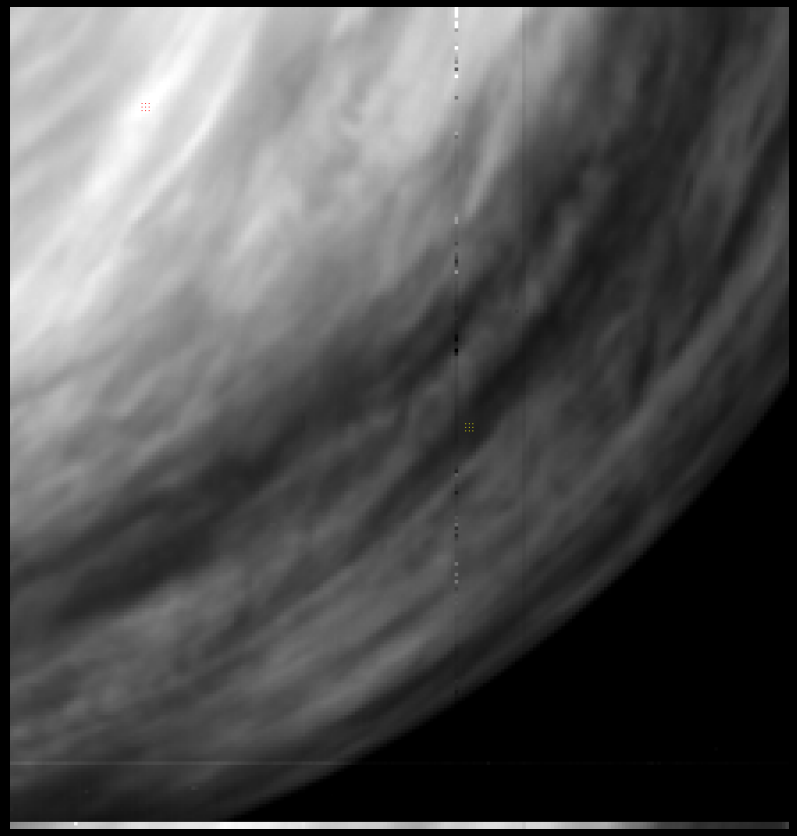
# Venus in near infrared



- This is an image from the Venus Express spacecraft, currently orbiting Venus.

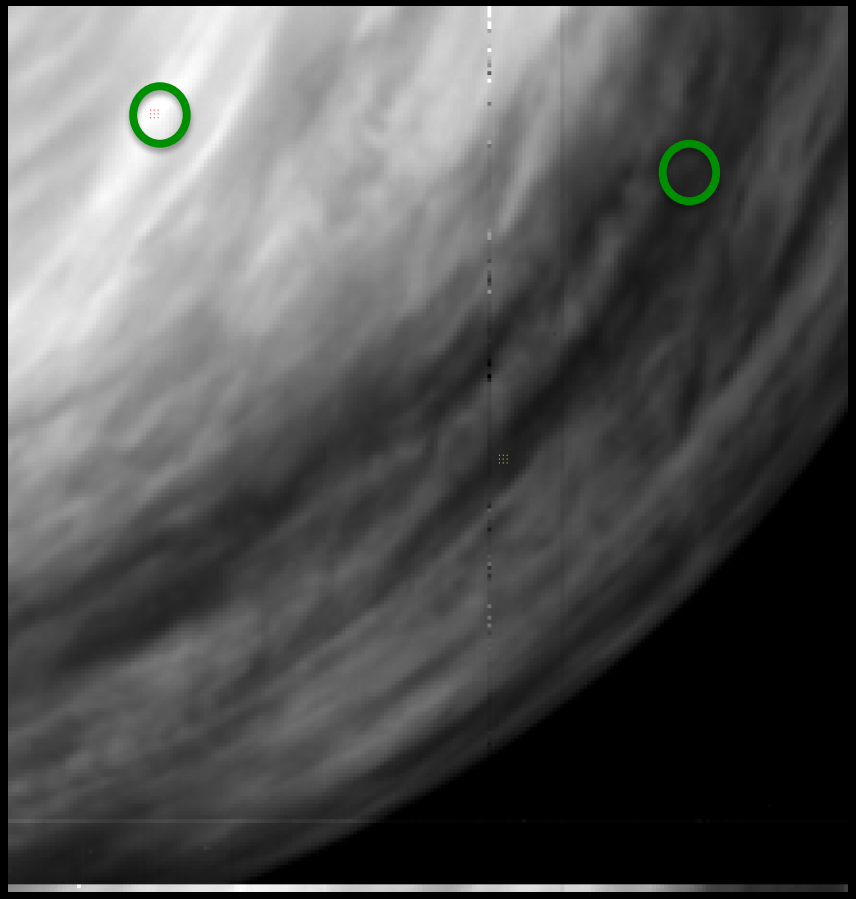
# Venus in near infrared

**Actual Data**

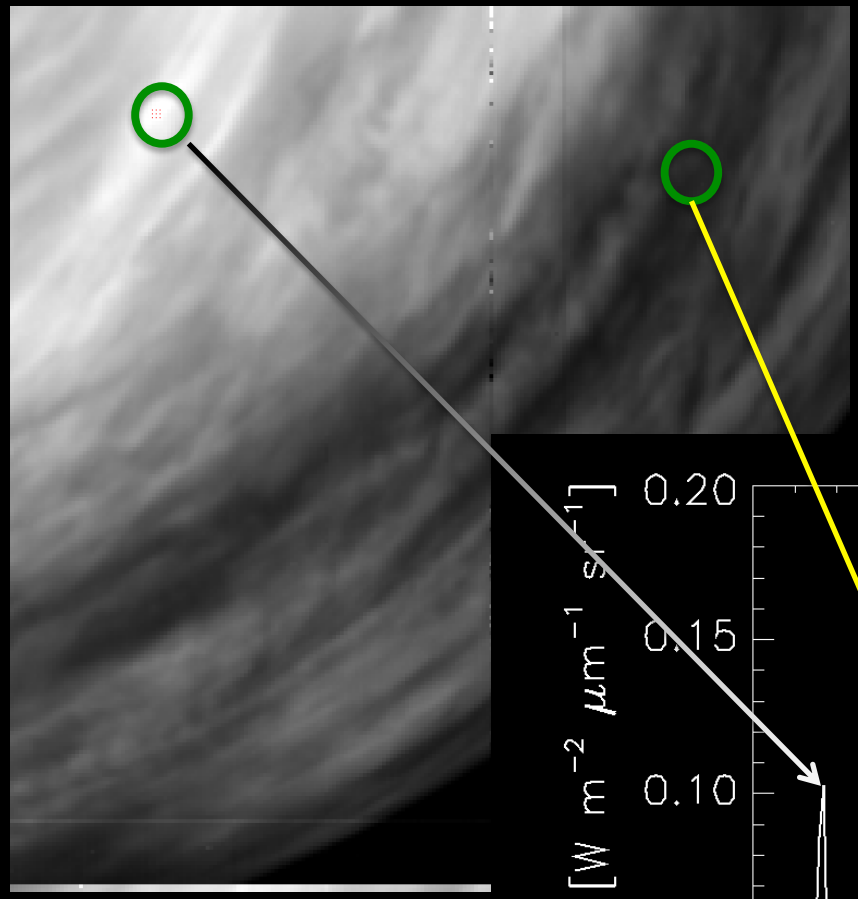


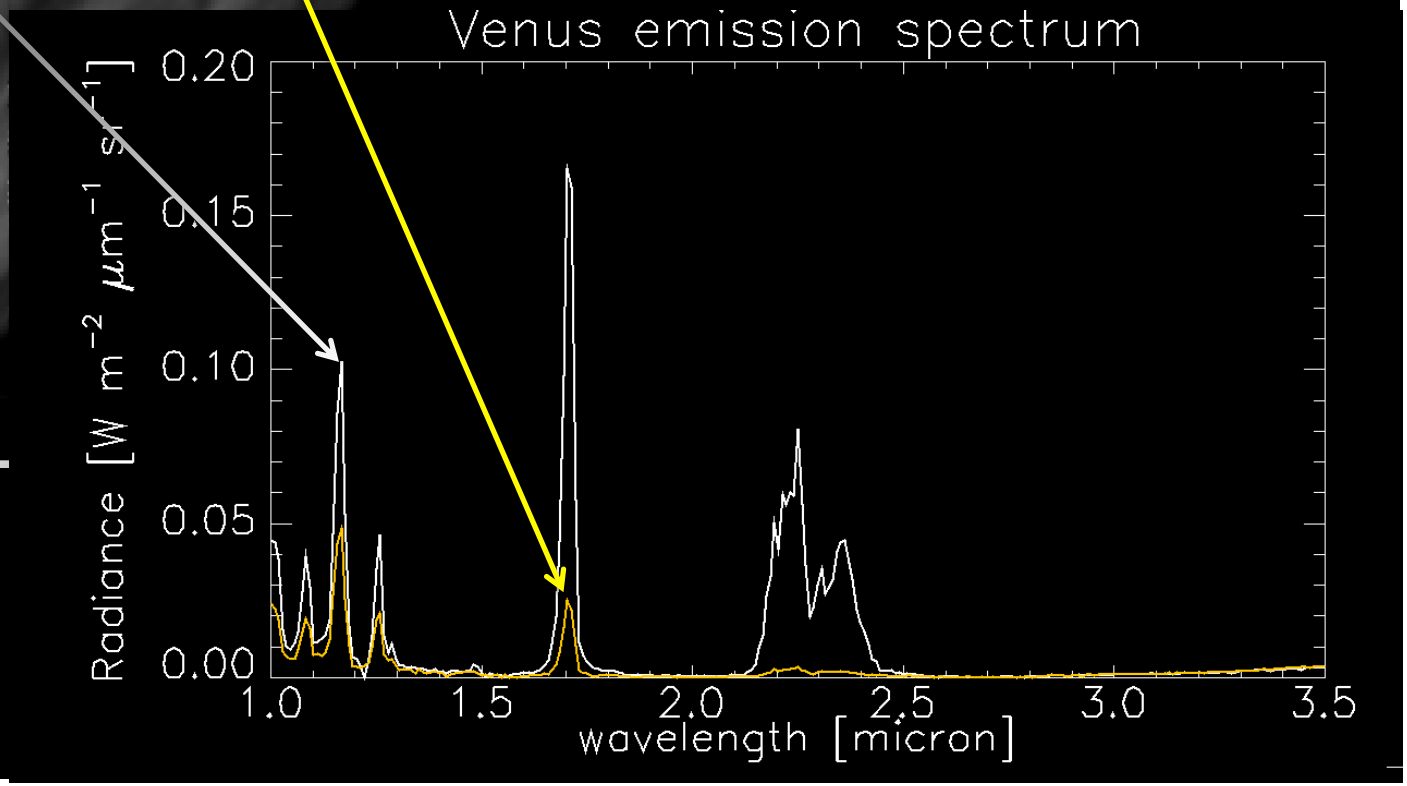
**Photonegative**

# Venus in near infrared

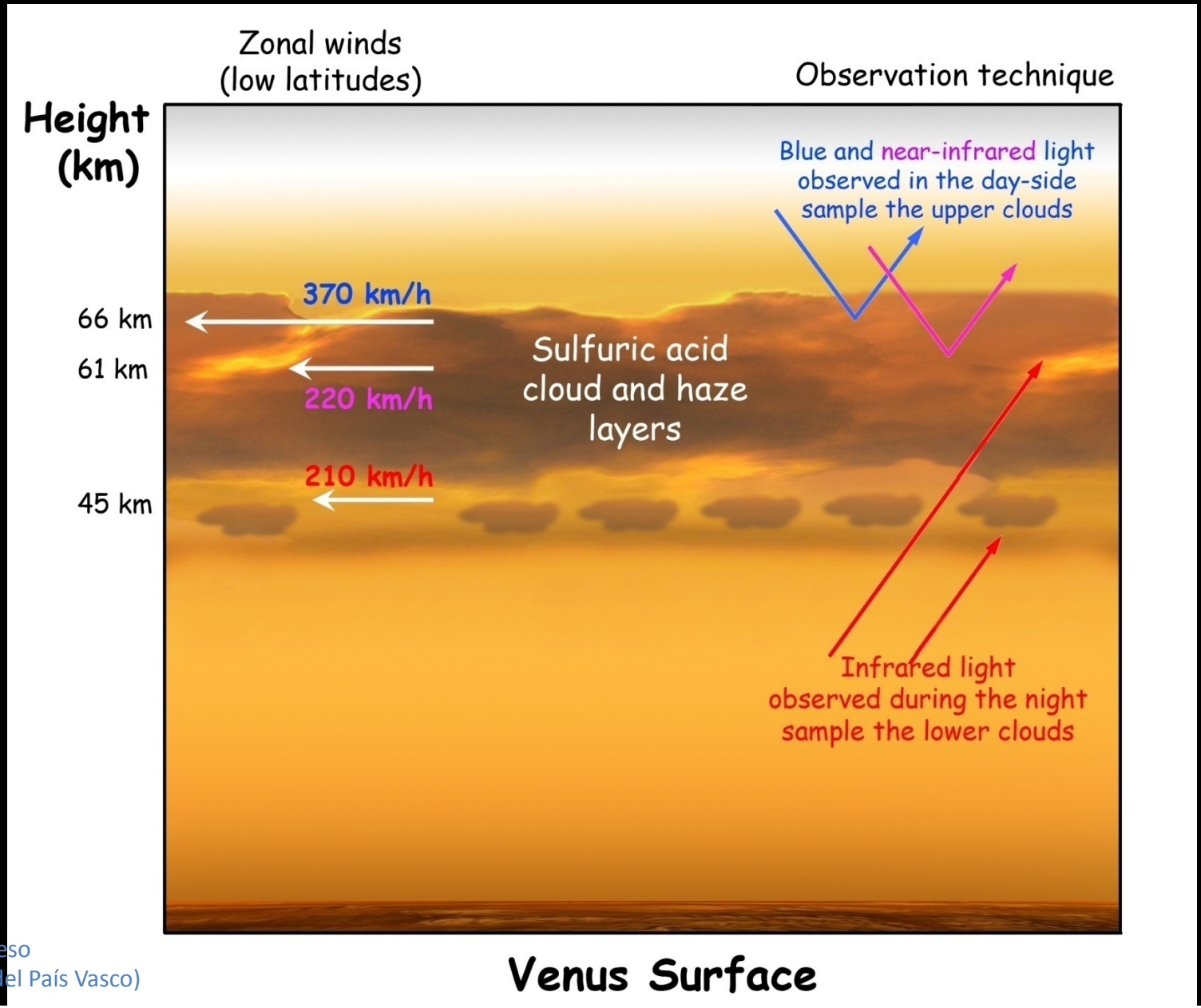


# Venus in near infrared



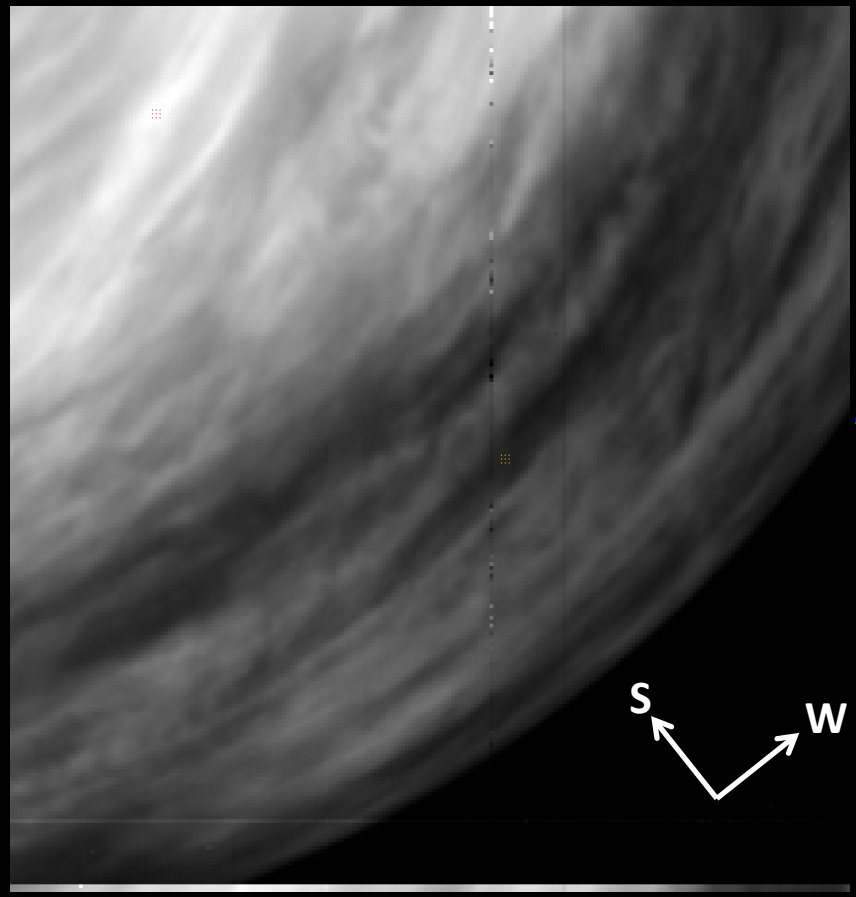


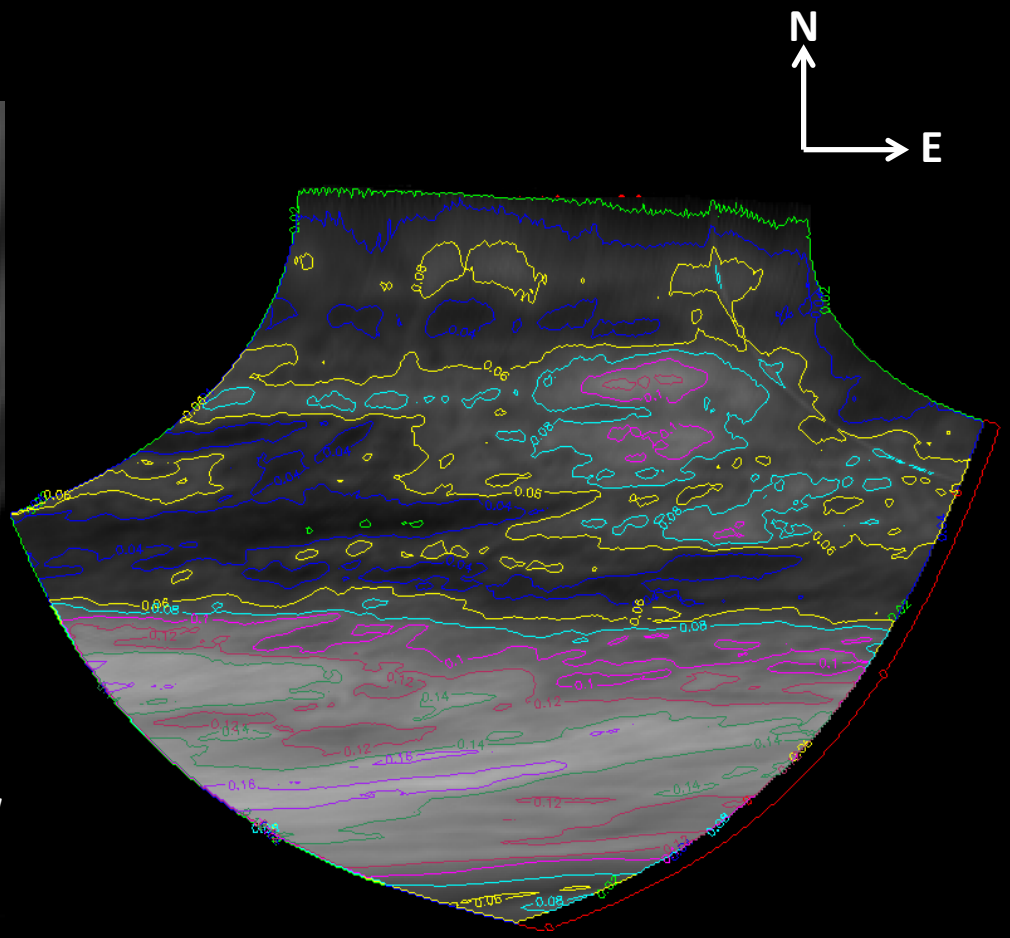
# Measure winds at different altitudes



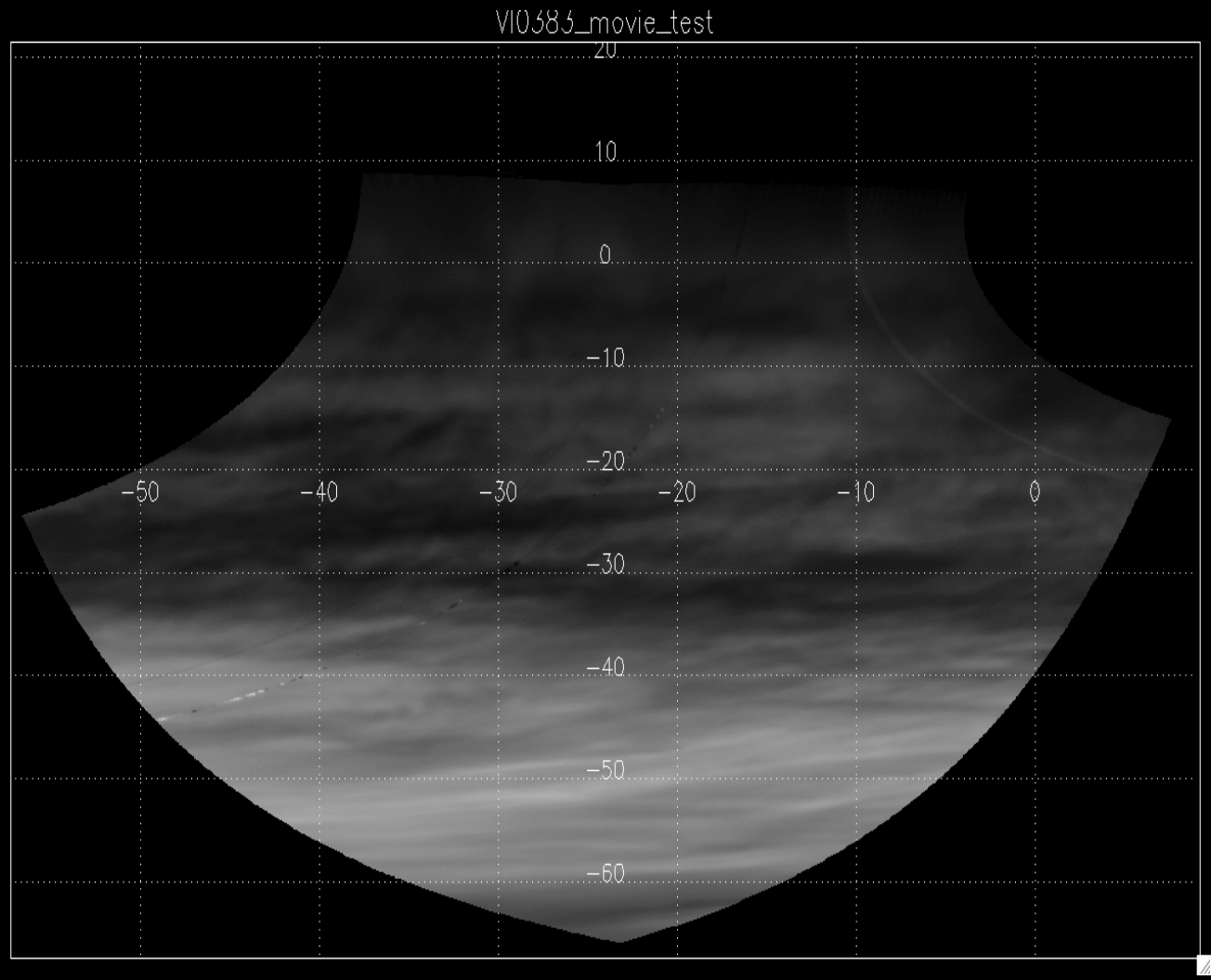

Credits: R. Hueso
(Universidad del País Vasco)

# Re-orient Image to Cartesian

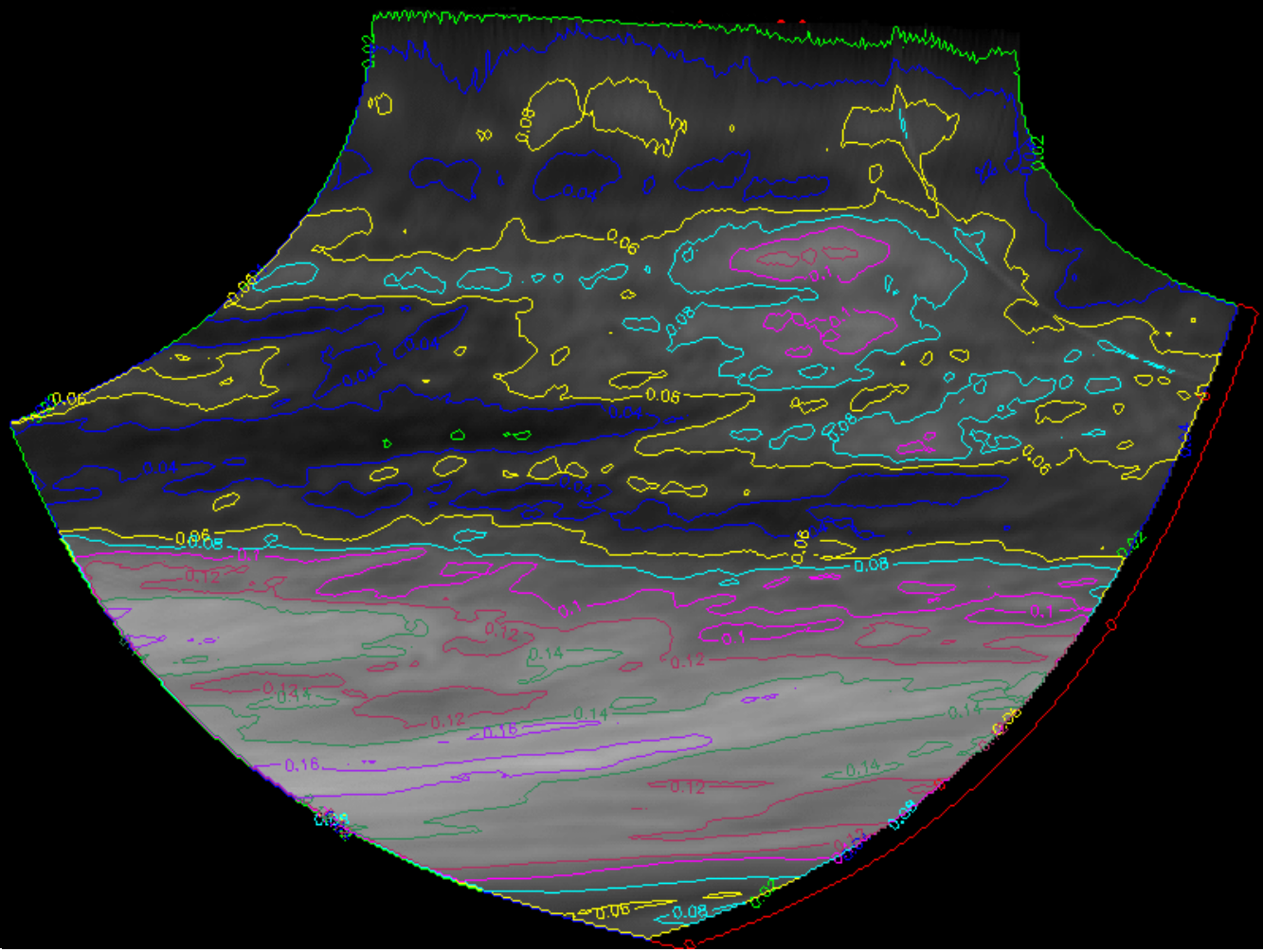


# Measuring the winds of Venus



# Six hours of Venus Meteorology



# 2012 Transit of Venus

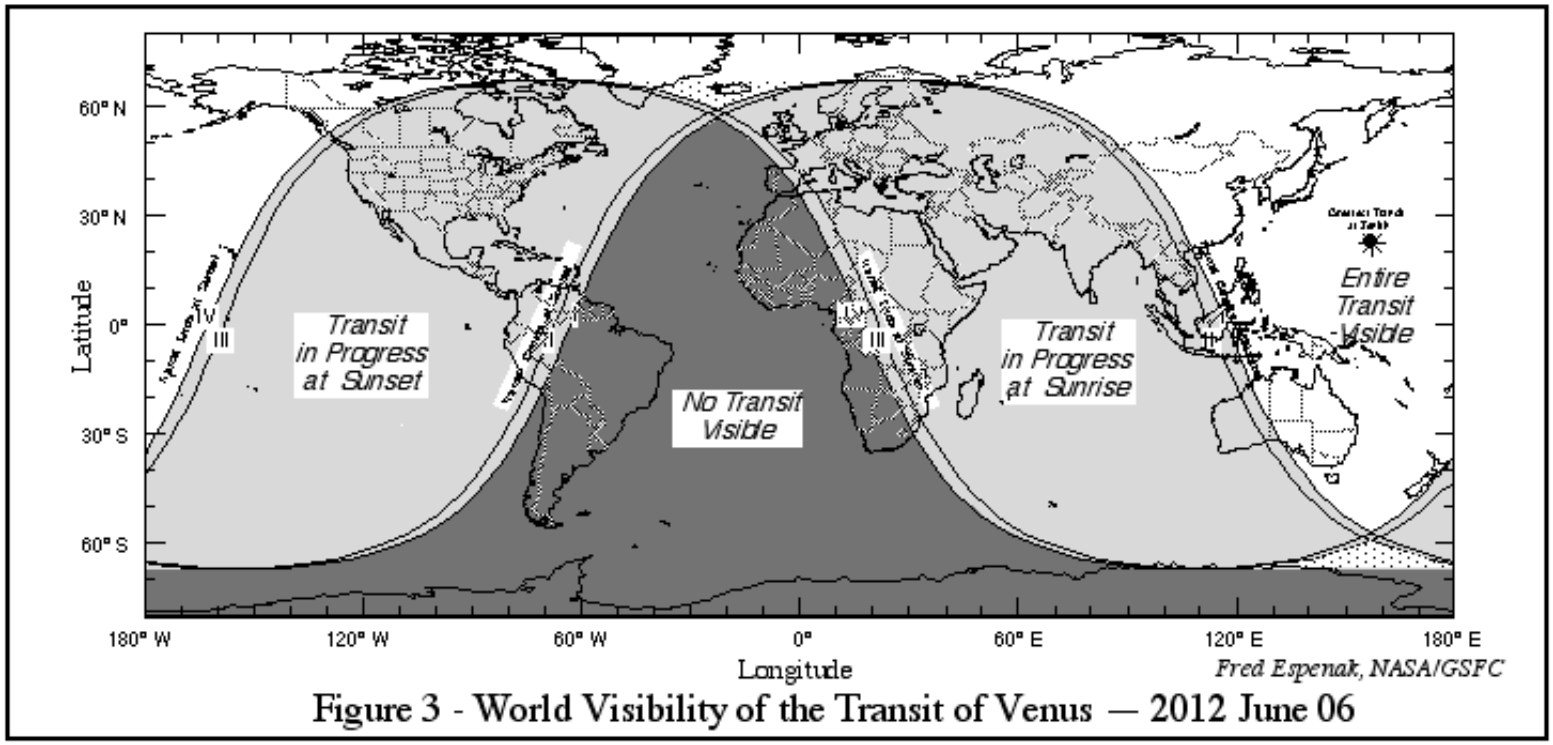



Figure 3 - World Visibility of the Transit of Venus — 2012 June 06

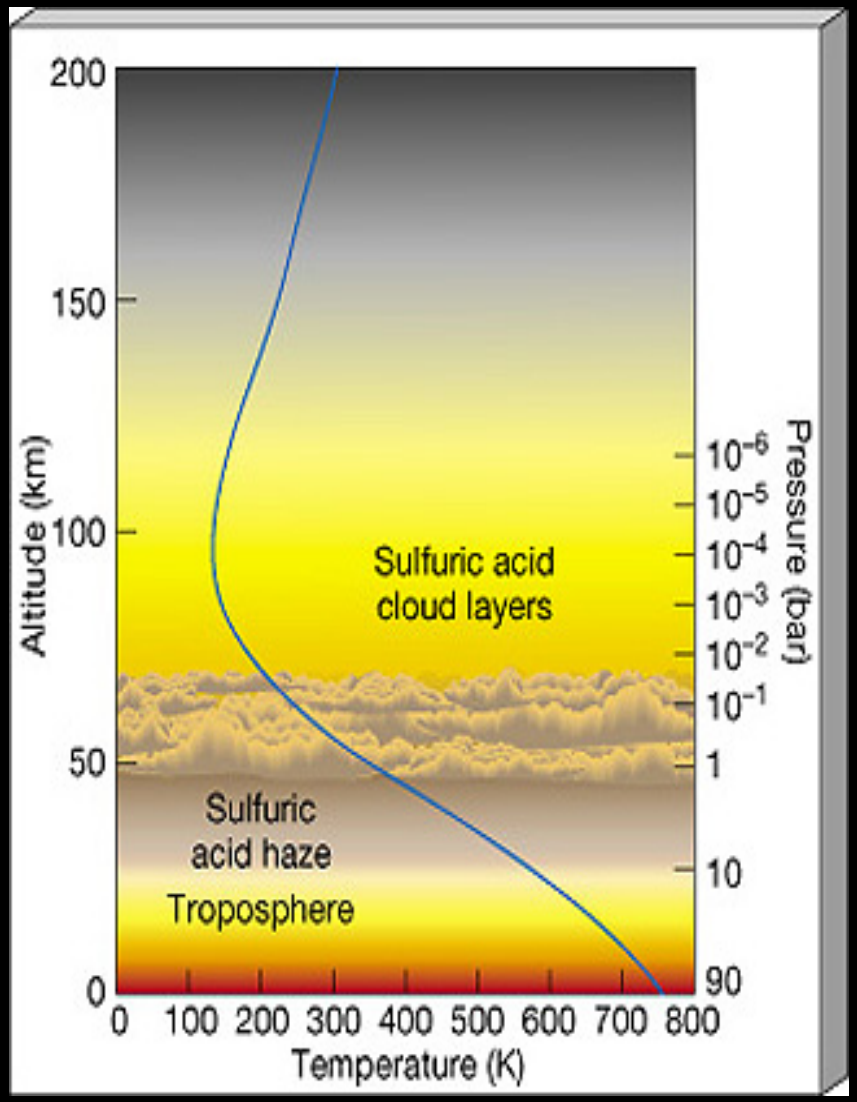
1st contact: 22:05:11 UTC (16:05:11 MDT), sun elevation: 47°

2nd contact: 22:22:47 UTC (16:22:47 MDT), sun elevation: 44°

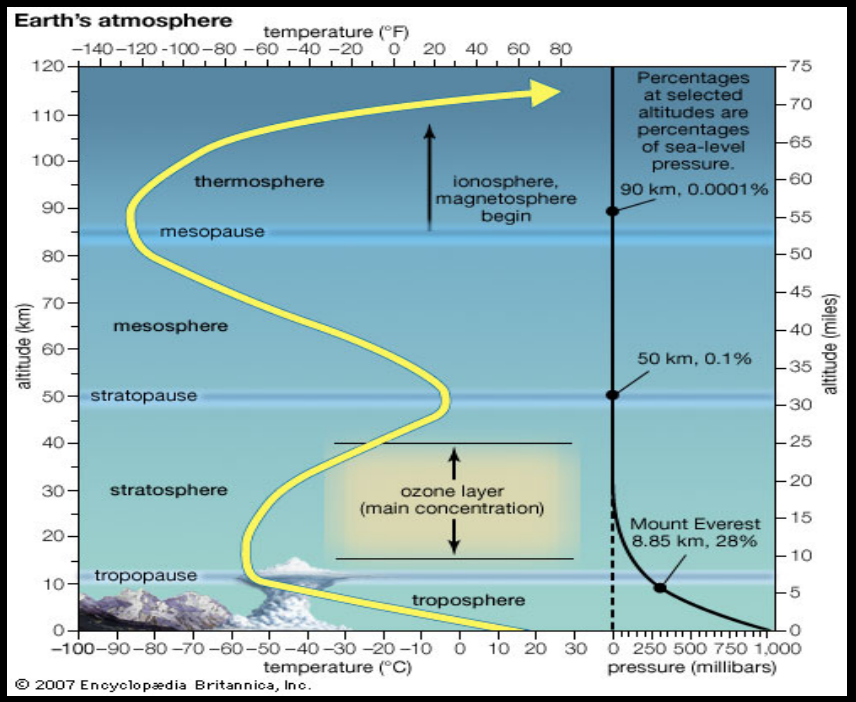
center time of transit: 01:25:36 UTC, 6/6 (19:25:47 MDT), sun el: 9°


Image Courtesy J. Whatmore / ESA

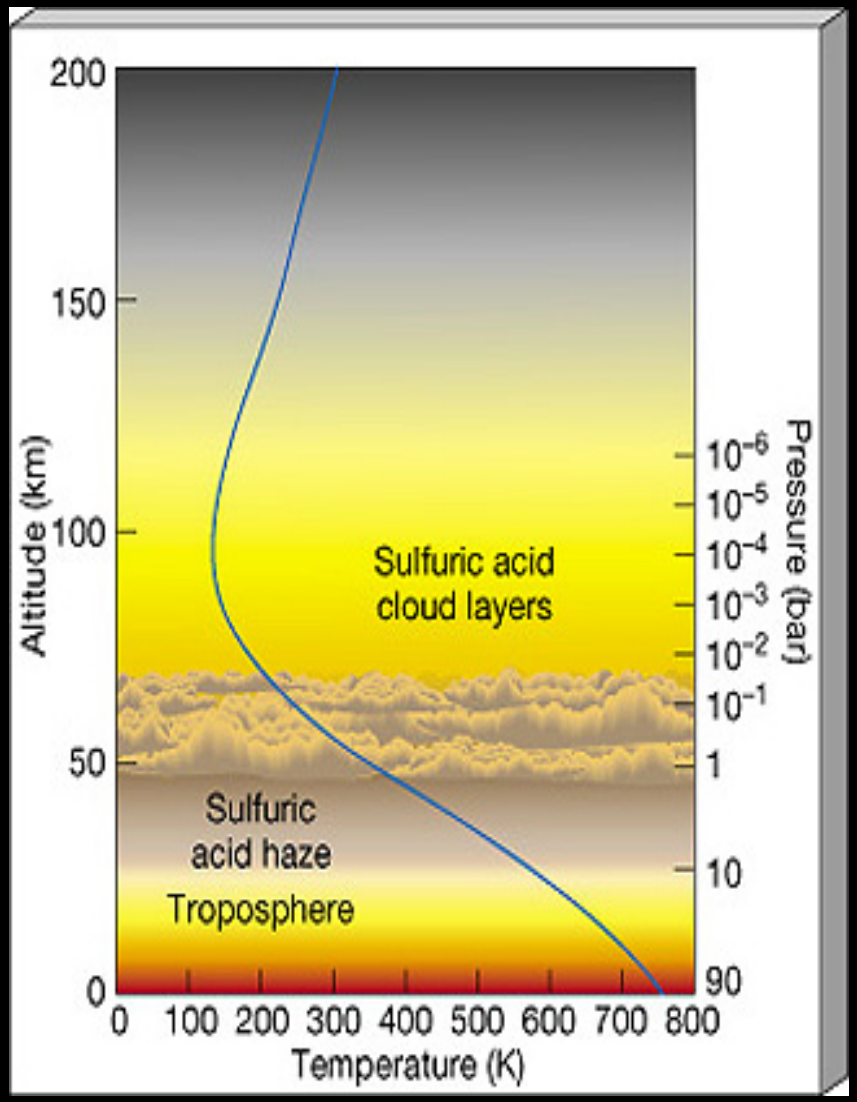
# Venus


200
150
100
50
0
Altitude (km)
Sulfuric acid
cloud layers
Sulfuric
acid haze
Troposphere
0 100 200 300 400 500 600 700 800
Temperature (K)
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
1
10
90
Pressure (bar)

# Earth


Earth's atmosphere
temperature (°F)
−140 −120 −100 −80 −60 −40 −20 0 20 40 60 80
thermosphere
ionosphere, magnetosphere begin
mesopause
mesosphere
stratopause
stratosphere
ozone layer (main concentration)
tropopause
troposphere
Percentages at selected altitudes are percentages of sea-level pressure.
90 km, 0.0001%
50 km, 0.1%
Mount Everest 8.85 km, 28%
altitude (km)
altitude (miles)
temperature (°C)
pressure (millibars)
© 2007 Encyclopædia Britannica, Inc.

# Venus


200
150
100
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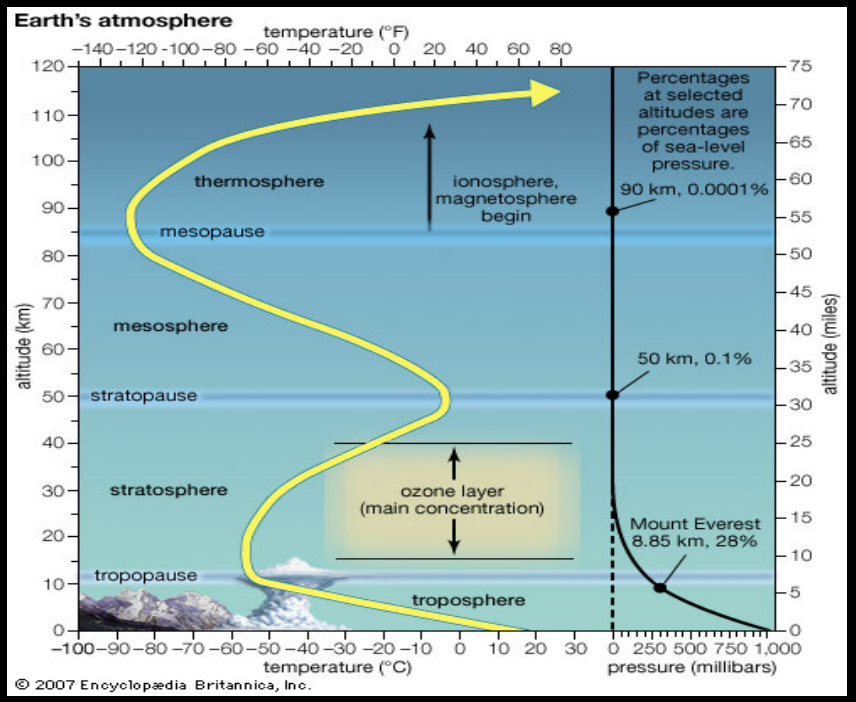
Altitude (km)
Sulfuric acid
cloud layers
Sulfuric
acid haze
Troposphere
0 100 200 300 400 500 600 700 800
Temperature (K)
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
1
10
90
Pressure (bar)

# Earth


Earth's atmosphere
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thermosphere
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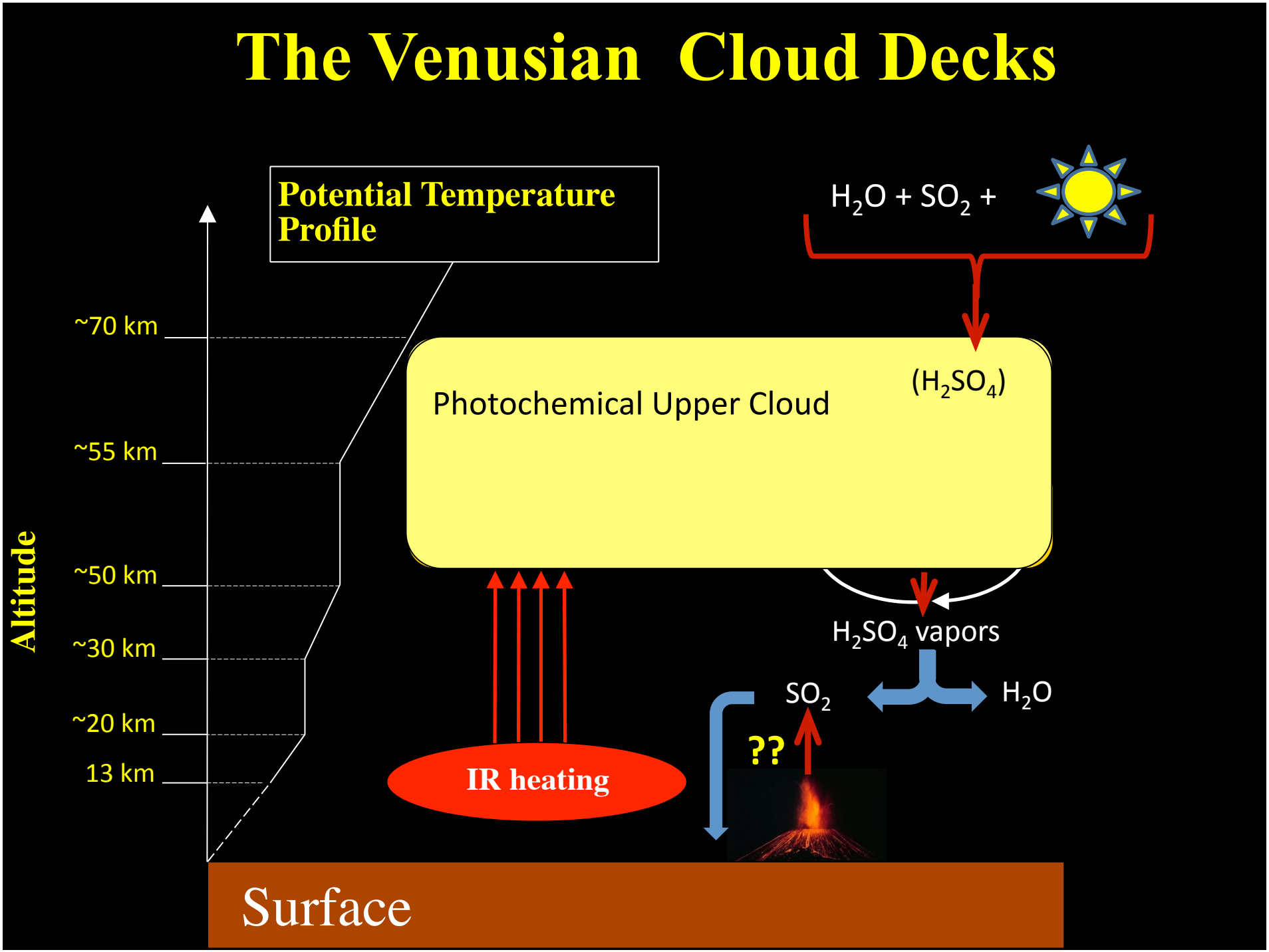
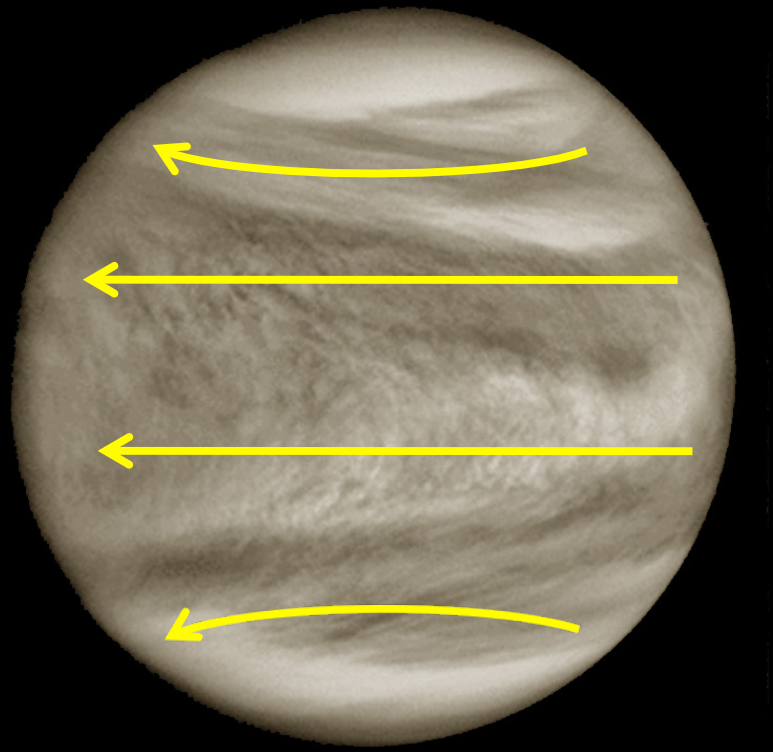
stratosphere
ozone layer (main concentration)
tropopause
troposphere
Percentages at selected altitudes are percentages of sea-level pressure.
90 km, 0.0001%
50 km, 0.1%
Mount Everest 8.85 km, 28%
altitude (km)
altitude (miles)
−100 −90 −80 −70 −60 −50 −40 −30 −20 −10 0 10 20 30
temperature (°C)
0 250 500 750 1,000
pressure (millibars)
© 2007 Encyclopædia Britannica, Inc.

# The Venusian Cloud Decks



# Venus Atmospheric Dynamics

## Super-rotation



- At cloud tops (75 km), 4 day East-to-West period!
  - About 400 kph (~250 mph)
  - Earth's jet stream, at its fastest, barely reaches these speeds!
- Wind at surface nearly 0 m/s
- Peak wind speed near 70 km
- Driver is uncertain!
  - Most of Solar Radiation is absorbed at the altitudes of the clouds

# How to determine the mass of the Sun

Newton's Law of Gravitation:

$$F = \frac{Gm_1m_2}{r^2}$$

Newton's 2nd Law (on Earth)

$$\frac{GM_\oplus m_{object}}{R_\oplus^2} = m_{object}g$$

$$G = \frac{gR_\oplus^2}{M_\oplus}$$

Newton's 2nd Law:

$$F = ma$$

Replace G in Kepler's 3rd Law:

$$\frac{gR_\oplus^2}{M_\oplus} \cdot \frac{M_\Sigma}{4\pi^2} = \frac{d_\oplus^3}{P_\oplus^2}$$

Circular Acceleration:

$$a = \frac{v^2}{r} \qquad v = \frac{2\pi d_\oplus}{P_\oplus}$$

$$\frac{GM_\Sigma M_\oplus}{d_\oplus^2} = M_\oplus \frac{4\pi^2 d_\oplus}{P_\oplus^2}$$

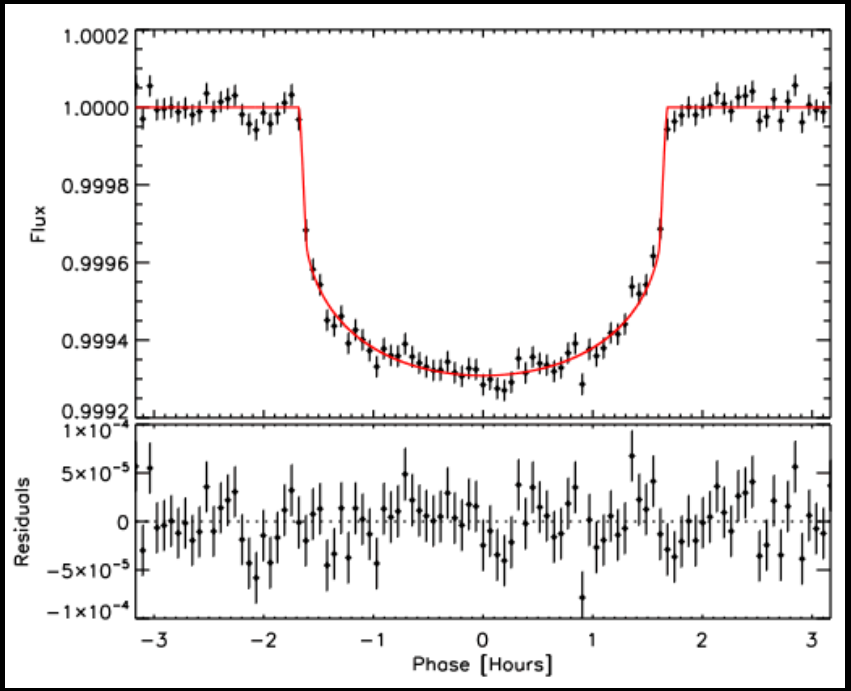
$$\frac{M_\Sigma}{M_\oplus} = \frac{4\pi^2}{gR_\oplus^2} \cdot \frac{d_\oplus^3}{P_\oplus^2}$$

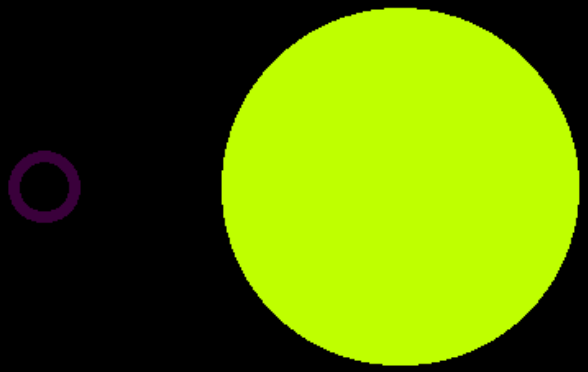
Kepler's 3rd Law

$$\frac{GM_\Sigma}{4\pi^2} = \frac{d_\oplus^3}{P_\oplus^2}$$

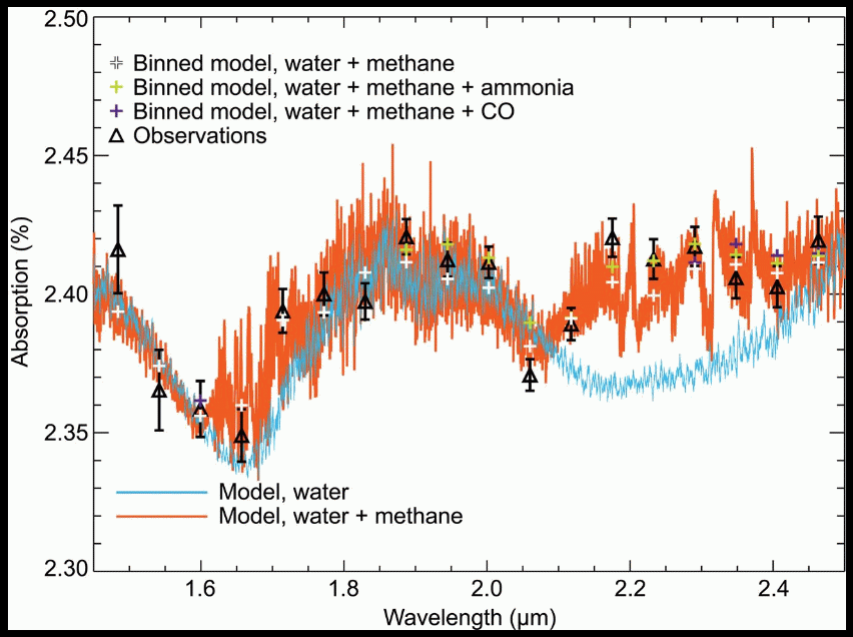
| $D_{sun}$ | $M_{sun}/M_{earth}$ |
|---|---|
| 300 $R_{earth}$ | 0.7 |
| 1,000 $R_{earth}$ | 26 |
| 3,000 $R_{earth}$ | 700 |
| 10,000 $R_{earth}$ | 26,000 |

# Transiting Planet with Atmosphere



# Transiting Planet with Atmosphere



# Mayan Calendar

- Venus (Kukulcan) features prominently in Mayan culture and calendar; many appearances of Venus are recorded in the “Dresden Codex”.

Image from the Dresden Codex (page 9).
Adapted from the 1880 edition by Förstemann.

# Mayan Calendar

Image from the Dresden Codex (page 9).
Adapted from the 1880 edition by Förstemann.

- Venus (Kukulcan) features prominently in Mayan culture and calendar; many appearances of Venus are recorded in the "Dresden Codex".
- However, the end of the world was NOT predicted by the Mayans to occur on 21 December 2012. That is simply the end of the $13^{th}$ major cycle.