XVIII IAG/USP Advanced School on Astrophysics: Searching for Biomarkers in Exoplanet Atmospheres

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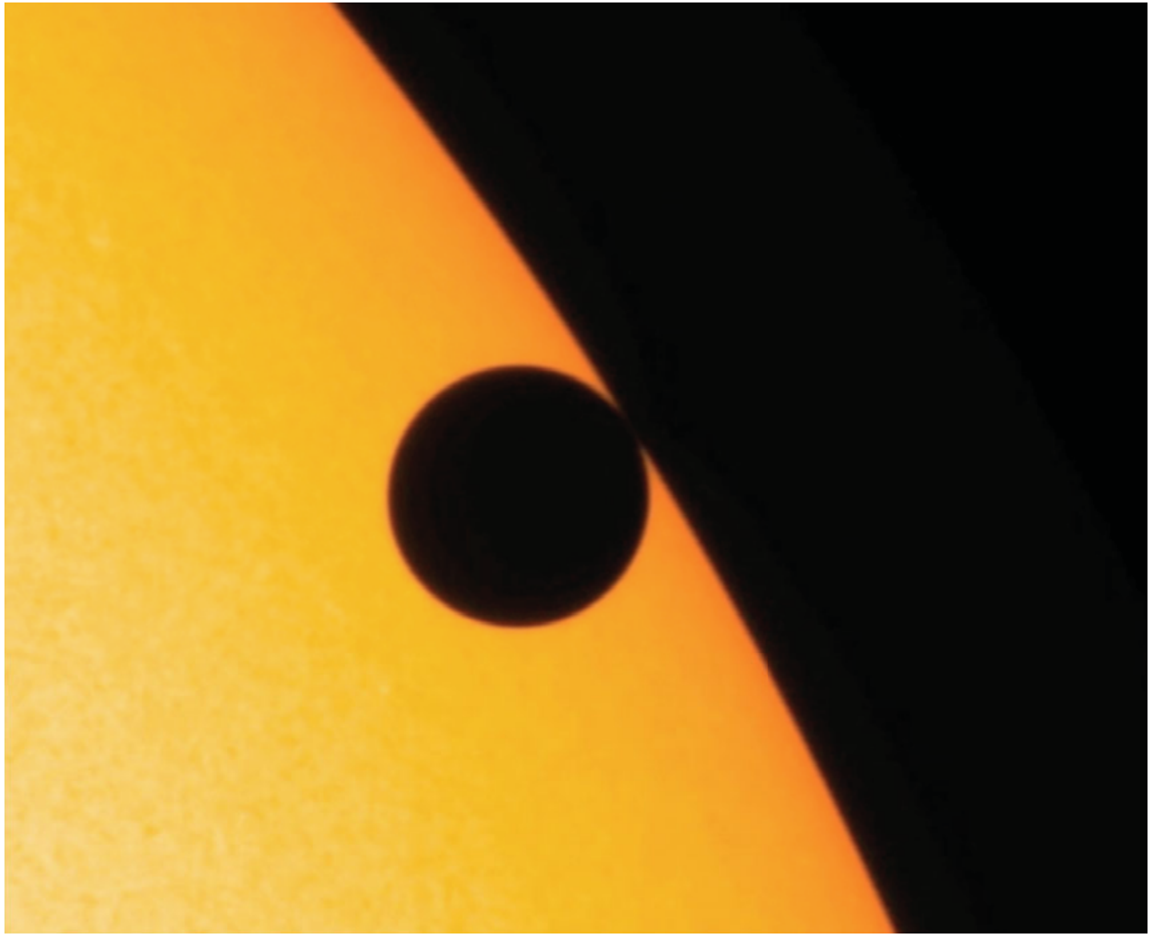
Harvard-Smithsonian Center for Astrophysics

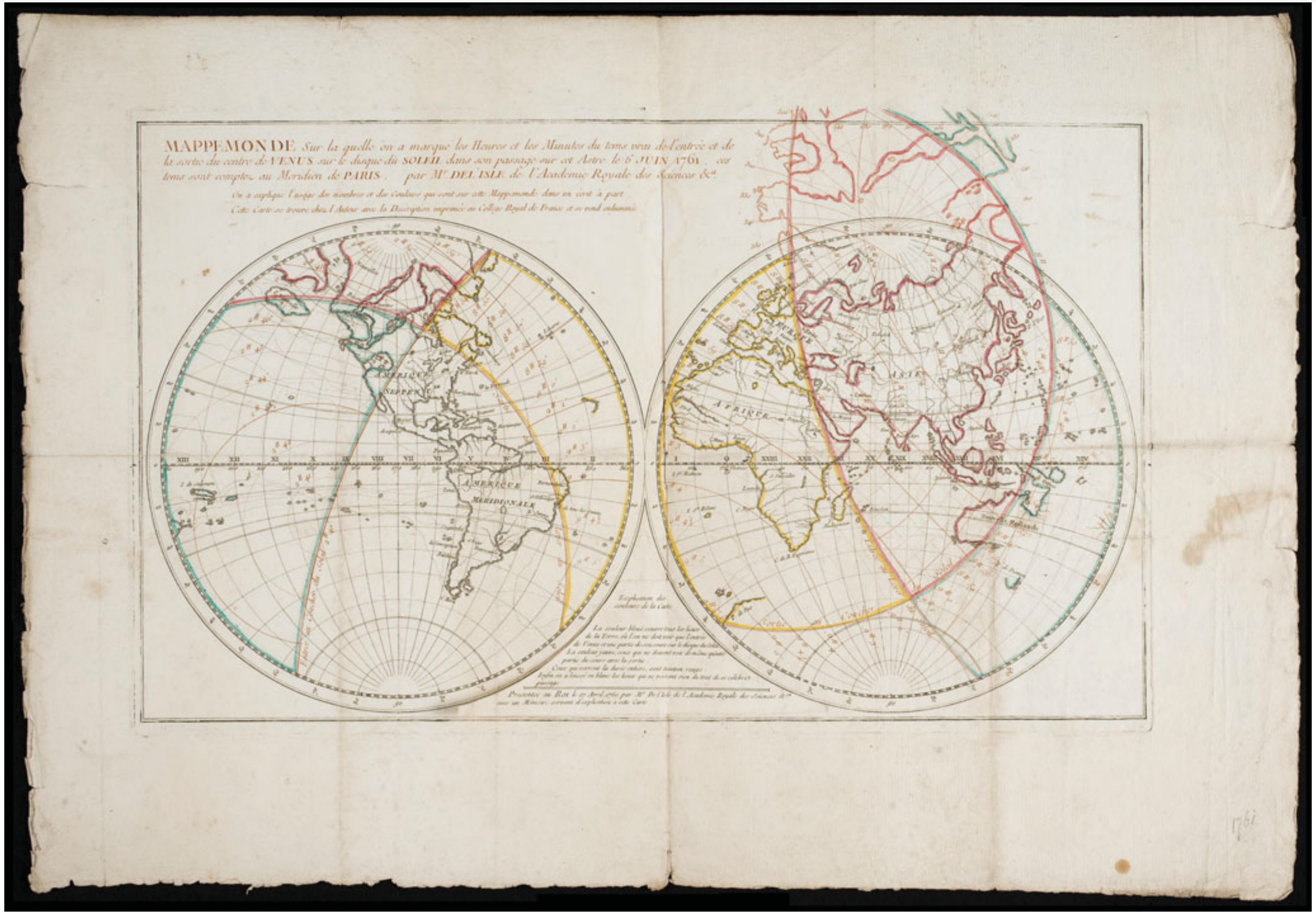
Universidad de Sao Paulo, 1 Mar 2018

The Discovery of Extraterrestrial Atmospheres: The Transit of Venus

7 Dec 1631	Predicted by Kepler.
4 Dec 1639	Observed by Horrocks and Crabtree.
6 June 1761	Global observational campaign incl. Lomonosov, Mason & Dixon.
3 June 1769	Global observational campaign incl. Capt. Cook, sent to Tahiti to observe.
9 Dec 1874	Global observational campaign, ”black drop” problem identified.
6 Dec 1882	John Phillip Sousa composed “Transit of Venus” march.
8 Jun 2004	
5-6 Jun 2012	
10-11 Dec 2117	Next transit of Venus.

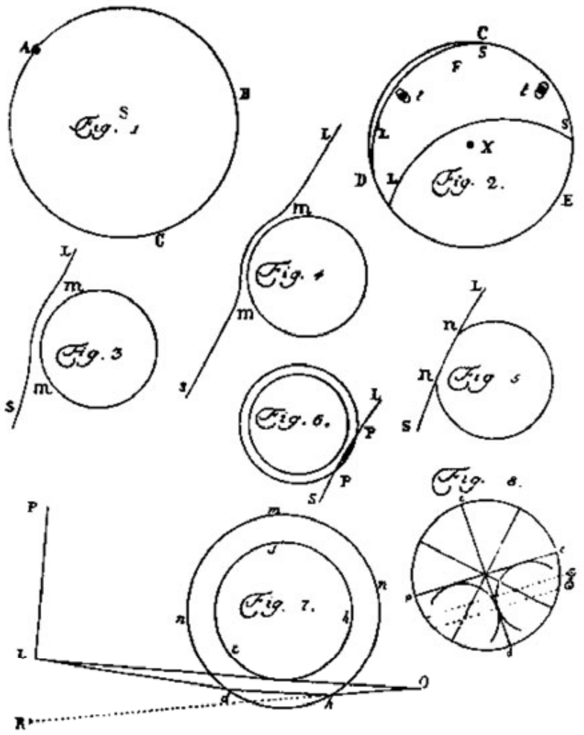


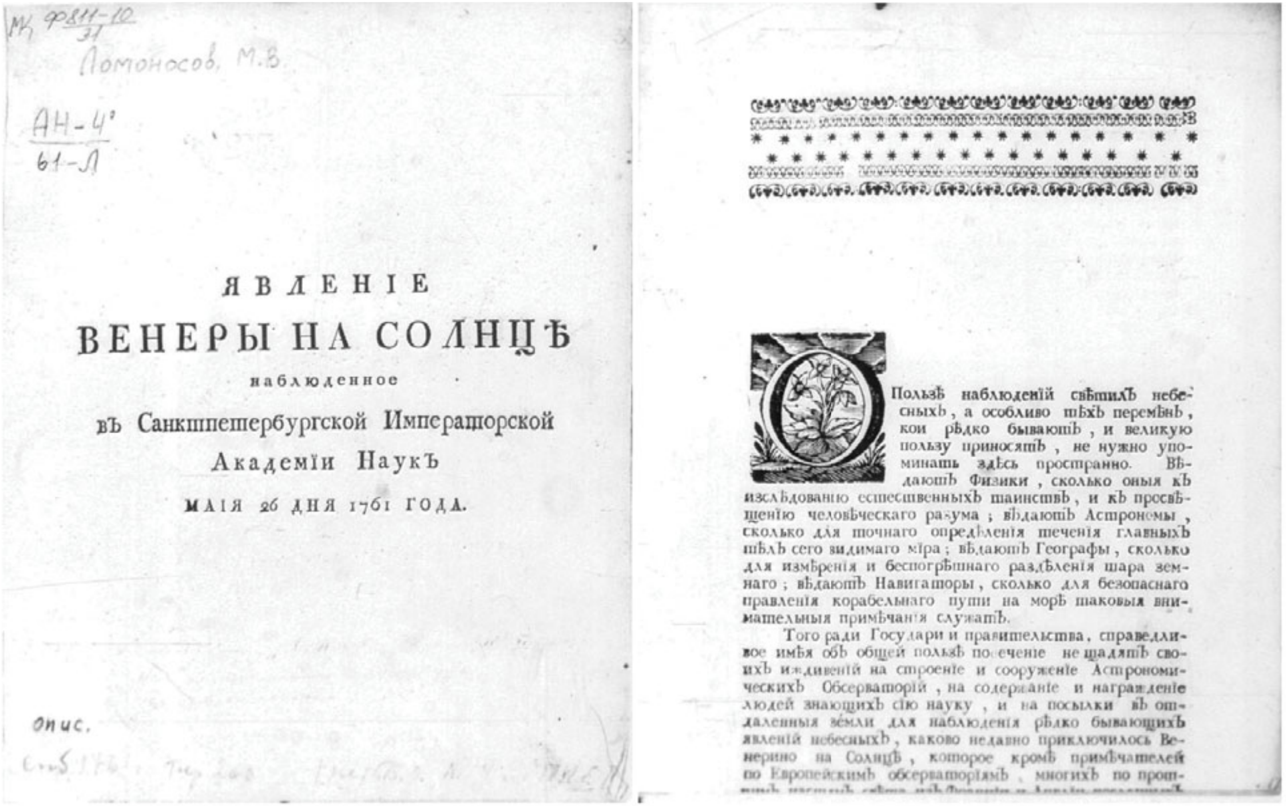
- Accurate measurement of times of second and third contact from widely separated global location permits direct measurement of the astronomical unit.
- Requires accurate geopositioning and timing (not so easy in 1761).



- Joseph-Nicolas Delisle sets up 62-station network for observing the transit.

Lomonosov and the discovery of Venus' atmosphere





Ломоносов, М.В.

АН-4°
61-Л

ЯВЛЕНІЕ
ВЕНЕРЫ НА СОЛНЦѢ
наблюденное
въ Санктпетербургской Императорской
Академіи Наукъ
МАІЯ 26 ДНЯ 1761 ГОДА.

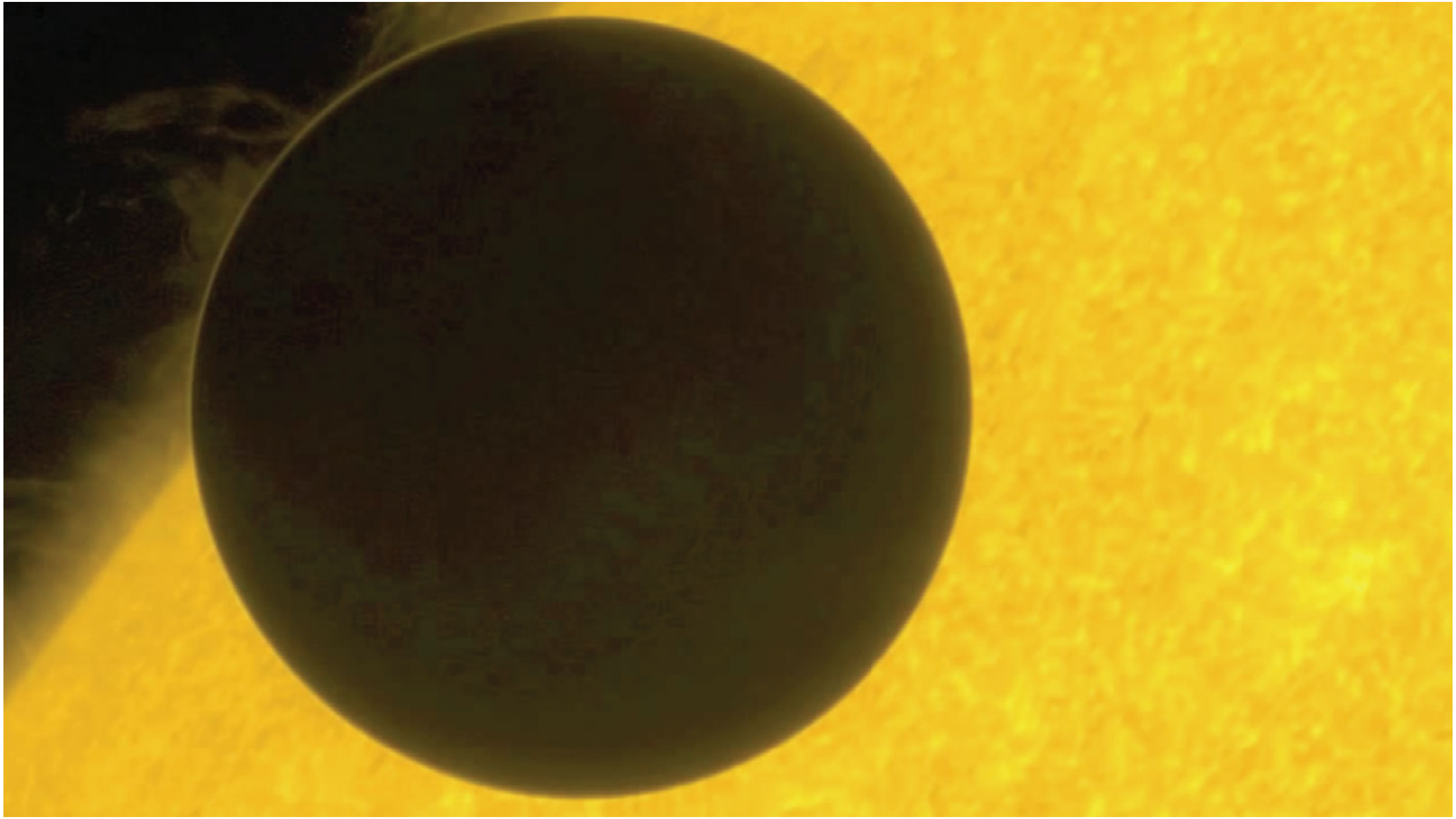
опис.

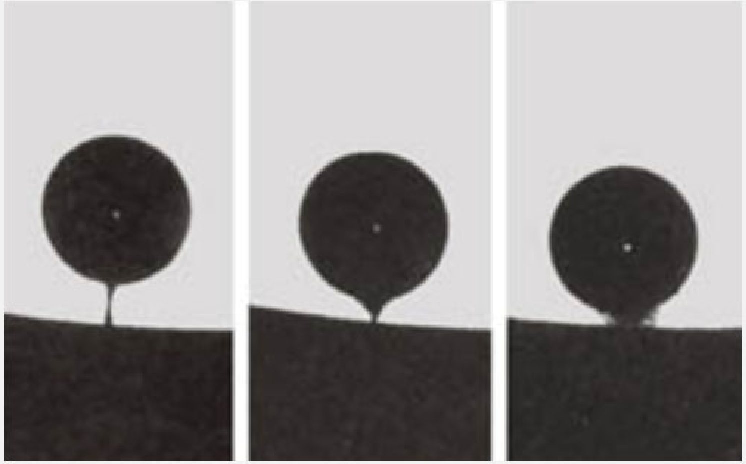
О Пользѣ наблюденій свѣтилъ небесныхъ, а особливо тѣхъ перемѣнъ, кои рѣдко бываютъ, и великую пользу приносятъ, не нужно упоминать здѣсь пространно. Вѣдаютъ Физики, сколько оныя къ изслѣдованію естественныхъ таинствъ, и къ просвѣщенію человѣческаго разума; вѣдаютъ Астрономы, сколько для точнаго опредѣленія теченія главныхъ тѣлъ сего видимаго міра; вѣдаютъ Географы, сколько для измѣренія и беспогрѣшнаго раздѣленія шара земнаго; вѣдаютъ Навигаторы, сколько для безопаснаго правленія корабельнаго пути на морѣ таковыя внимательныя примѣчанія служатъ.

Того ради Государи и правительства, справедливое имѣя объ общей пользѣ попеченіе, не щадятъ своихъ иждивеній на строеніе и сооруженіе Астрономическихъ Обсерваторій, на содержаніе и награжденіе людей знающихъ сію науку, и на посылки въ отдаленныя земли для наблюденія рѣдко бывающихъ явленій небесныхъ, каково недавно приключилось Венерино на Солнцѣ, которое кромѣ примѣчателей по Европейскимъ обсерваторіямъ, многихъ по прот-

- Distance measurement fails, but Mikhail Lomonosov find evidence of Venusian atmosphere.

Imaging the Atmosphere of Venus

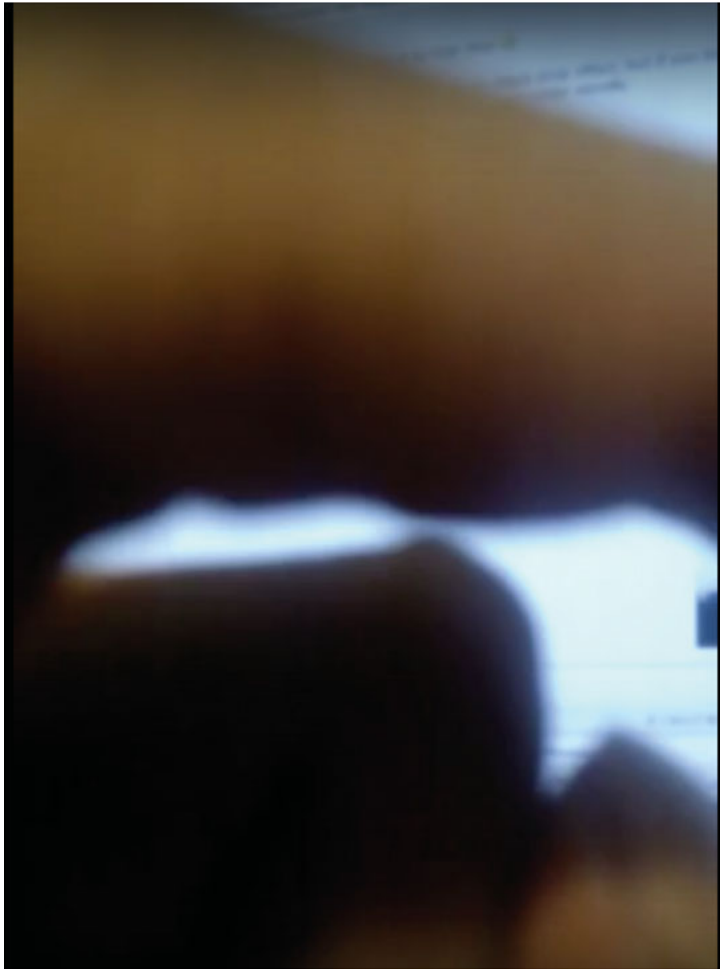


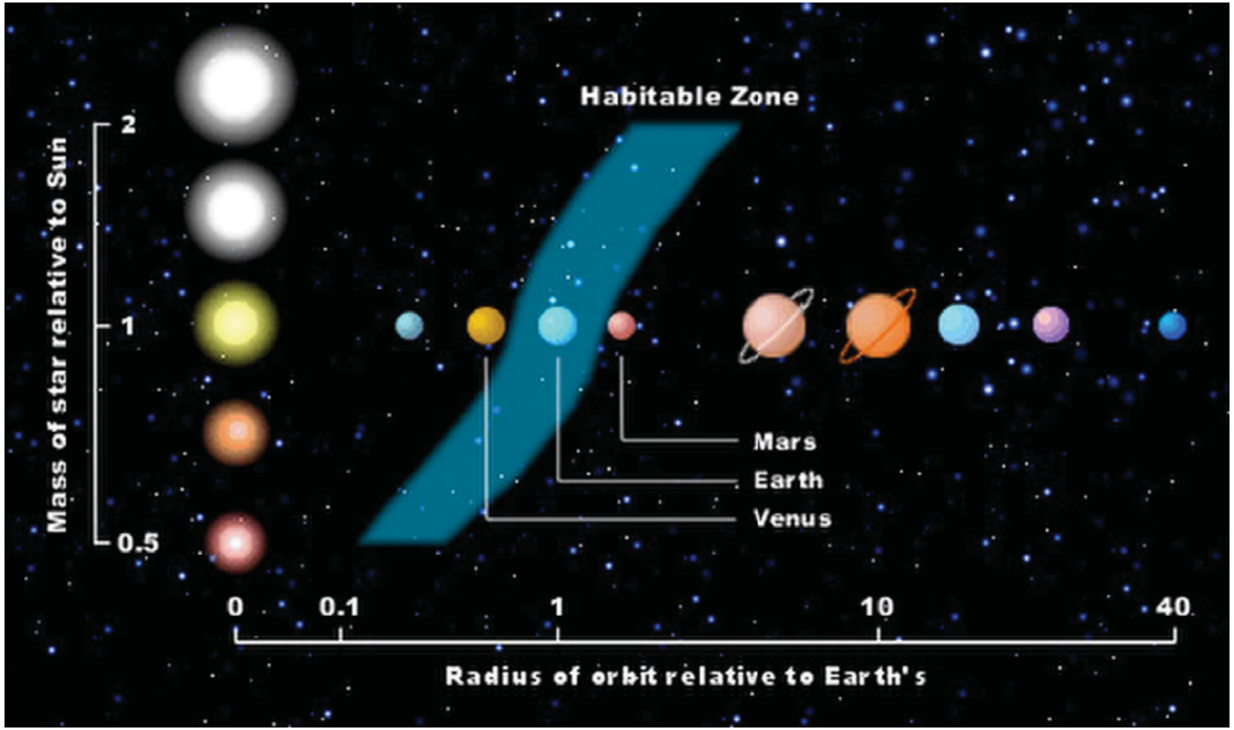


Australian watchmaker F. Allerding recorded the â€œblack-dropâ€ effect as the silhouette of Venus prepared to exit the Sunâ€™s disk on December 9, 1874. He observed through a 3½-inch refractor.

The "black drop" effect photographed during a transit of Mercury.

- The “black drop” effect limits measure of time of contacts to ± 1 minute
- Not an effect from Venus atmosphere – seen in transits of Mercury
- Combination of solar limb darkening and finite point response function of optics





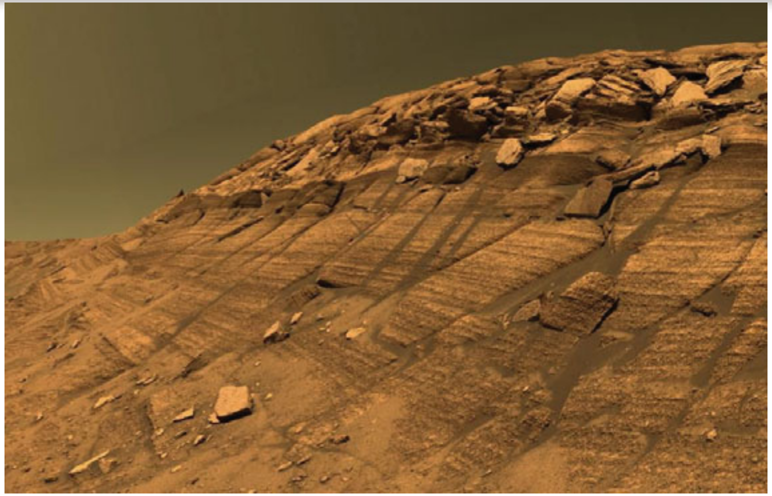
- The habitable zone is “fuzzy”.
- Atmospheric effects contribute to planetary surface temperature
- Solar luminosity has increased on Gy timescales.
- Mars & Venus are “almost” in the habitable zone.
- Note habitable zone depends strongly on stellar type.


OVER 100 TIMES DENSER THAN MARS' ATMOSPHERE
78% NITROGEN
21% OXYGEN
1% OTHER
Earth
96% CARBON DIOXIDE
<2% ARGON
<2% NITROGEN
<1% OTHER
Mars

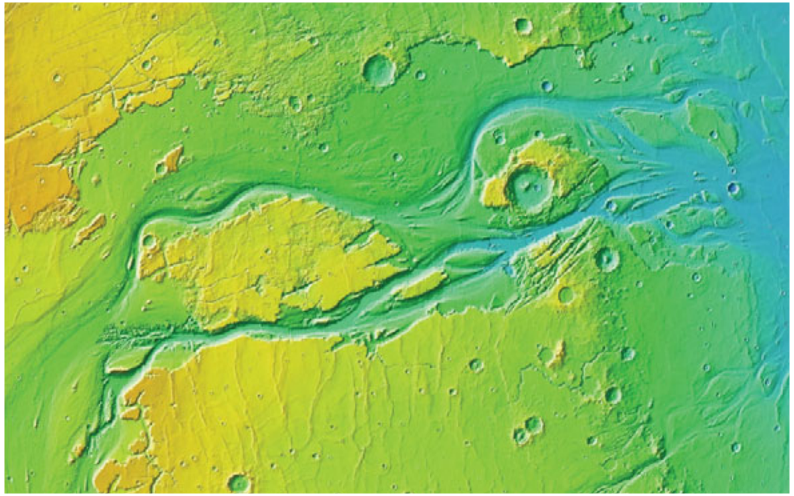
Psychrophile: Xanthoria elegans (lichen) capable of photosynthesis at -24°C.

Pyrococcus Furious: Optimal environment T=100°C near hydrothermal vents.

Is Mars Habitable? Evidence for Water on Mars in the Past



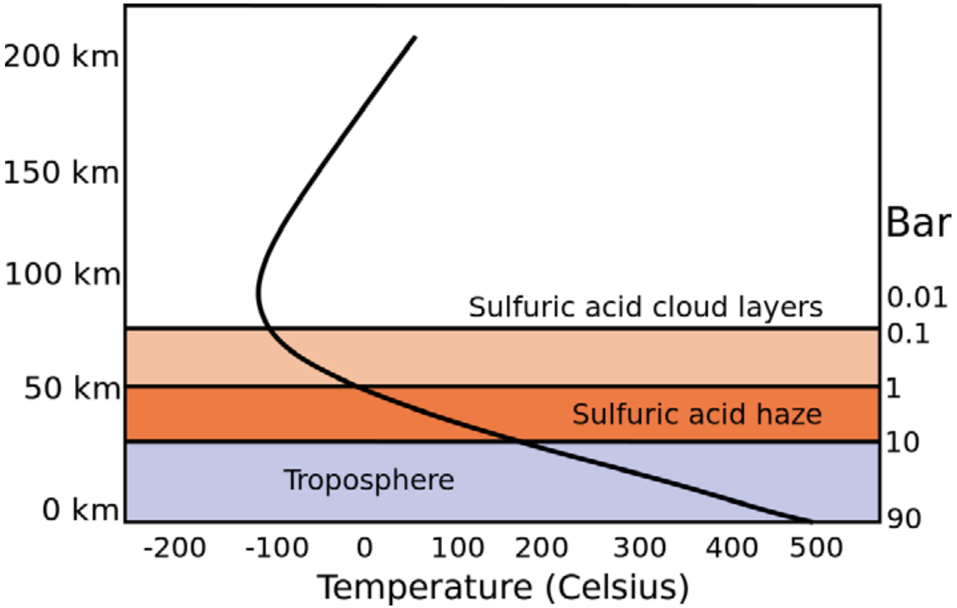
- Stratigraphy

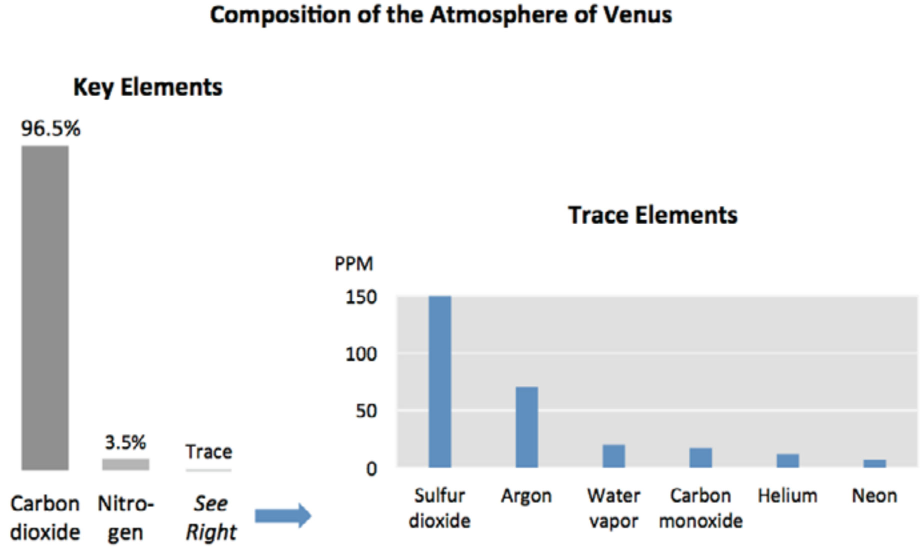


- Topography

- Mars had abundant liquid water in the past.
- Some of that water is bound in subsurface ice.
- Subsurface saline water reservoirs (probably) exist.
- Mars habitability for extremophiles still an open question.

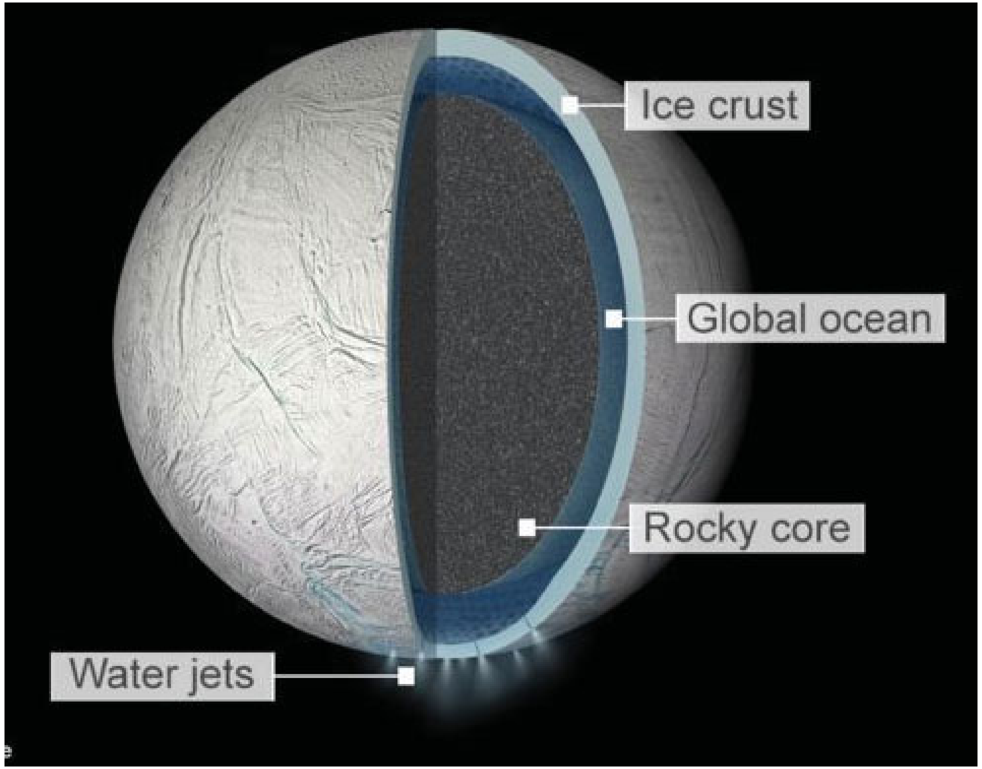
Arnold says “Not!”.

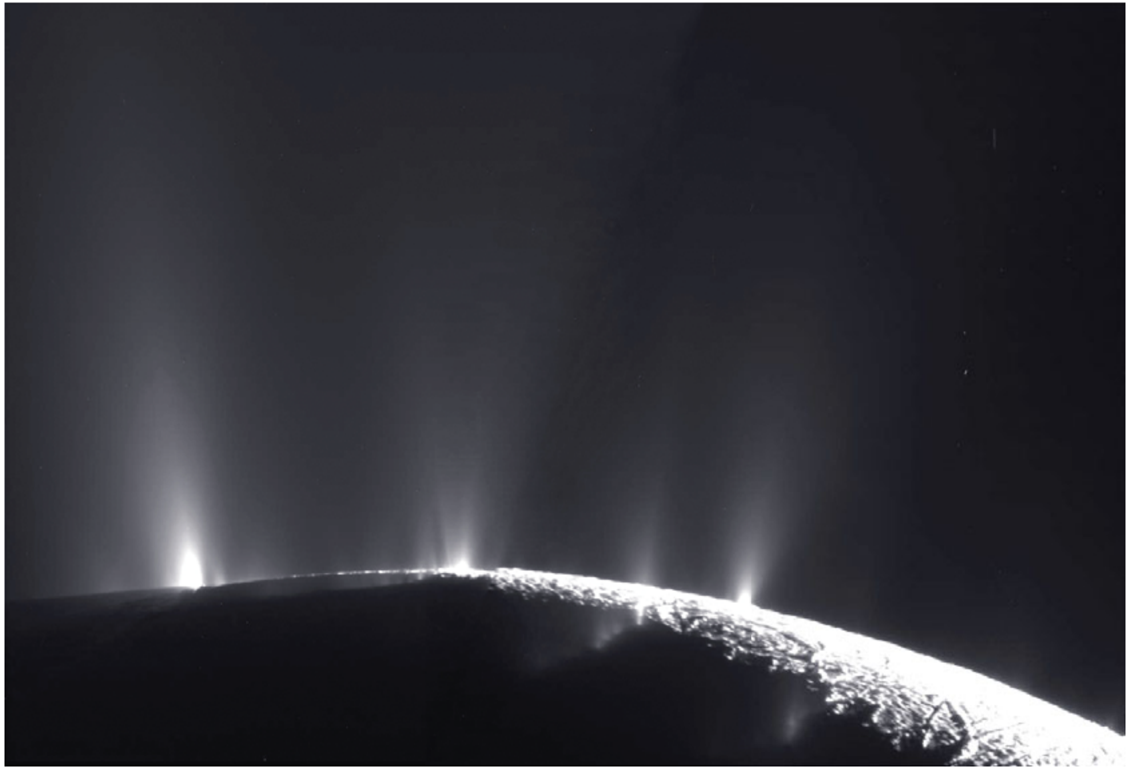




- Surface pressure ~90 × earth.
- Surface temperature ~500°C − to hot for know extremophiles.
- Upper layer of troposphere "super rotates".
    - $P_{Rot,atm}$ = 4 Earth days, $P_{Rot, Venus}$ = 243 Earth days.
- 3.8 Gya, Sun was 25% less luminous, Venus in Habitable Zone
- Venus was probably Earth-like with surface water.
- Runaway Greenhouse effect has evaporate all liquid water (n.b. Climate change deniers).

Habitability of Enceladus (Moon of Saturn)





- Cassini discovered plume of water emitted between cracks in Enelacus' icy crust.
- Evidence of large liquid water reservoir beneath crust which is tidally heated.

Article | OPEN

Biological methane production under putative Enceladus-like conditions

Ruth-Sophie Taubner, Patricia Pappenreiter, Jennifer Zwicker, Daniel Smrzka, Christian Pruckner, Philipp Kolar, Sébastien Bernacchi, Arne H. Seifert, Alexander Krajete, Wolfgang Bach, Jörn Peckmann, Christian Paulik, Maria G. Firneis, Christa Schleper & Simon K.-M. R. Rittmann

Nature Communications **9**, Article number: 748 (2018)
doi:10.1038/s41467-018-02876-y
Download Citation

Archaeal physiology | Astrobiology | Rings and moons

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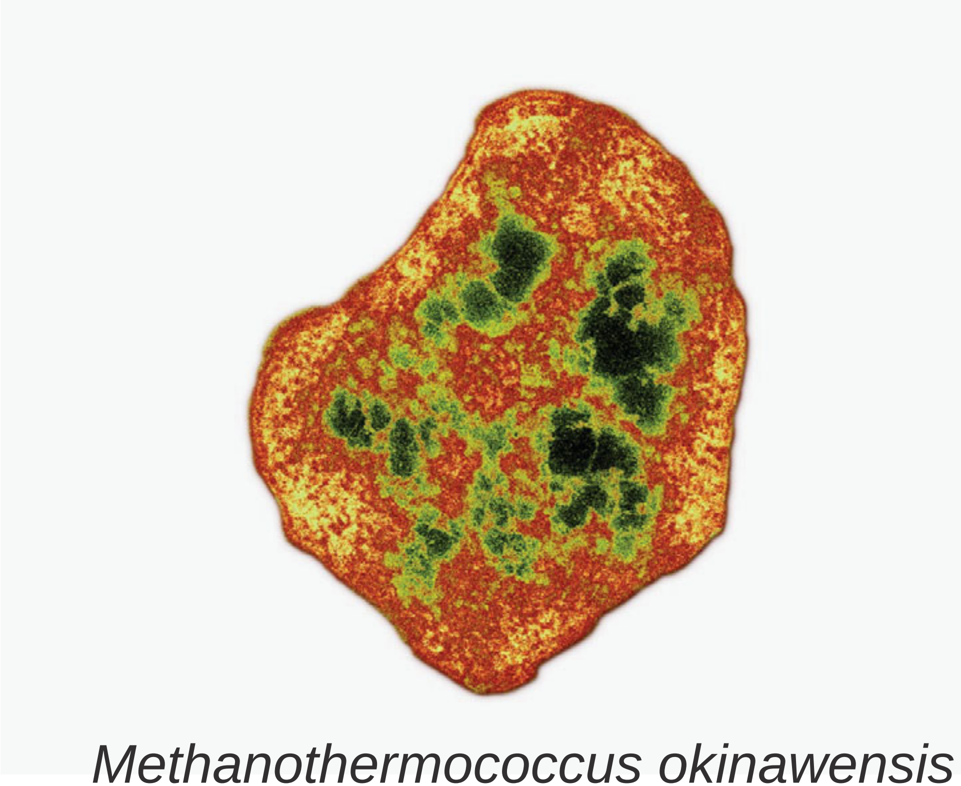
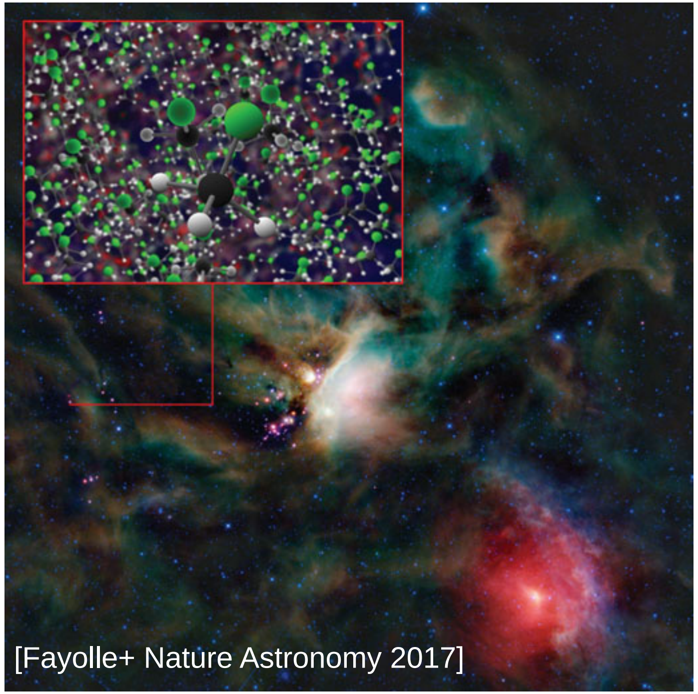
Published online: 27 February 2018



Methanothermococcus okinawensis

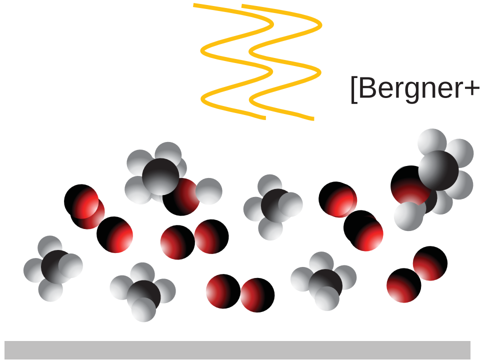
- Extremophiles survive (and thrive?) in lab recreation of Enceladus ocean environment.
- Could be used to “colonize” Enceladus.

2017: Interstellar organohalogens and a new pathway to astrochemical complexity


[Fayolle+ Nature Astronomy 2017]

CH_3Cl is common in protostars and comets, and on its own not a good bio-marker.

Based on laboratory experiments, CH_3OH can form from oxygen insertion in CH_4 ice, presenting a new pathway for complex organic molecule formation in interstellar ices at surprisingly low (<20 K) temperatures.


[Bergner+ 2017]

CH_4:O_2 ice mixture produces CH_3OH when exposed to UV light at 10 K through insertions of excited O atoms into CH_4

- Methanol (CH_3OH) is a potentially important precursor to biologically interesting molecules.
- Not a biomarker.

Understanding the Origins of Biomolecules – And Connects to Observations

The Astrophysical Journal Letters, 823:L10 (7pp), 2016 May 20
doi:10.3847/2041-8205/823/1/L10

CrossMark

FIRST DETECTION OF GAS-PHASE METHANOL IN A PROTOPLANETARY DISK

Catherine Walsh[1], Ryan A. Loomis[2], Karin I. Öberg[2], Mihkel Kama[1], Merel L. R. van 't Hoff[1], Tom J. Millar[3], Yuri Aikawa[4], Eric Herbst[5], Susanna L. Widicus Weaver[6], and Hideko Nomura[7]
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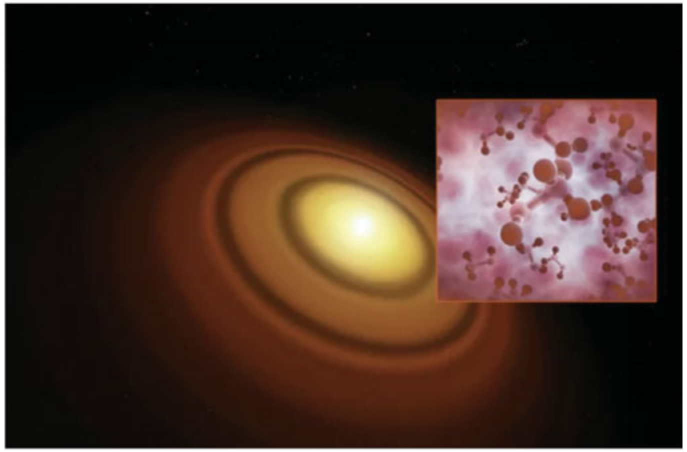
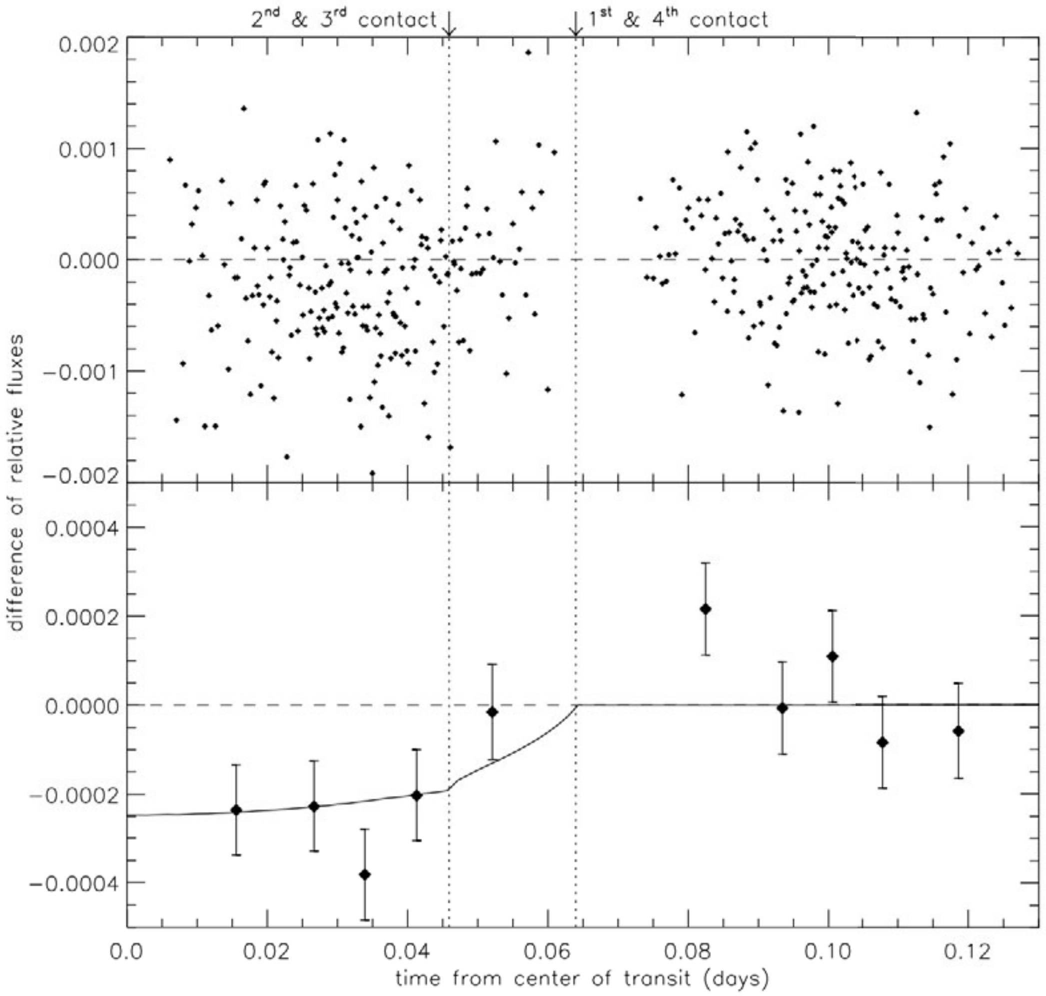
Received 2016 February 13; revised 2016 March 29; accepted 2016 April 4; published 2016 May 13



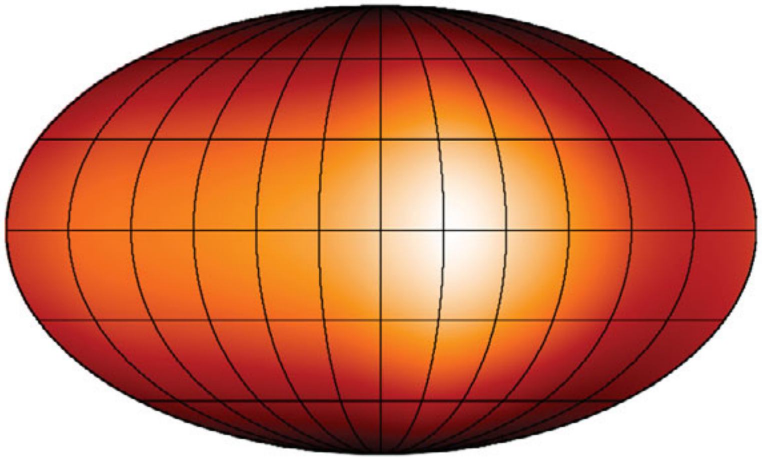
- Precusors to complex biomolecules may form in protoplanetary disks.
- Methanol survives comet–planet impacts.
- Processing to biomolecules may then proceed on planet surface.

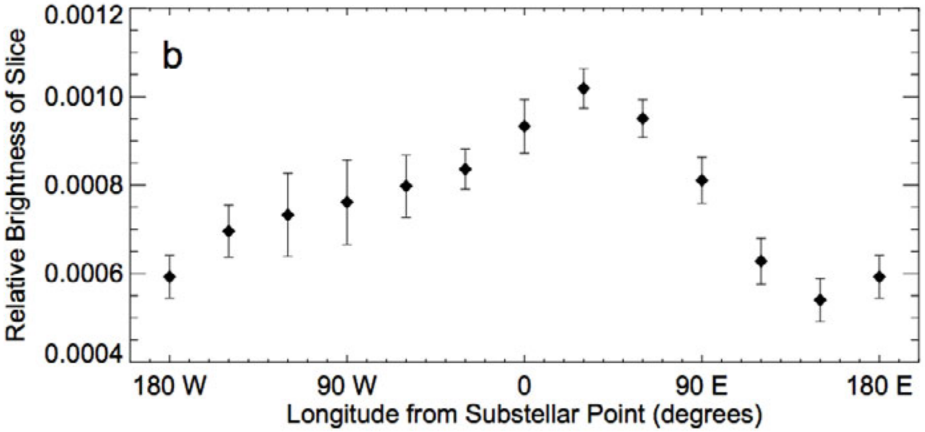
Exoplanet Atmospheres



- Transmission spectra of HD 209458b during transit.
- HST/STIS observation centered on Na D.
- Compare transit depth measure in Sodium D (5893Å) with depth is off-band.
- In-band is deeper than off-band, evidence of atmospheric Sodium.
- Compared with off-band, Na D absorption increases during transit.

Charbonneau, et al., 2001



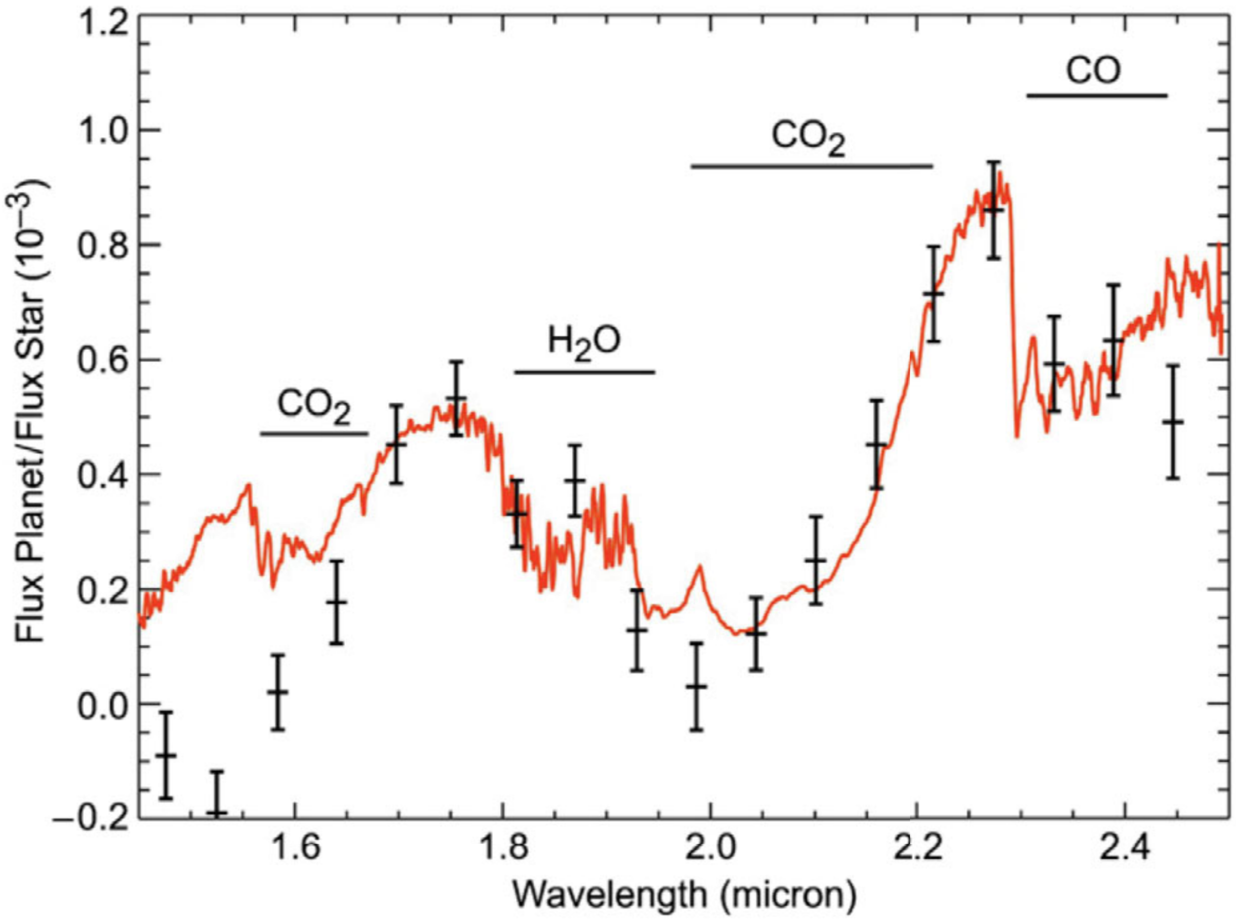


- 189733b: K2V, $m_K = 5.5$
- HD 189733b:
  - m = 1.16 M♃
  - $P = 2.22^d$
  - Hot Jupiter, tidally locked
- Data from Spitzer IRAC camera

The hottest longitude is not the sub-stellar point − evidence of global circulation.

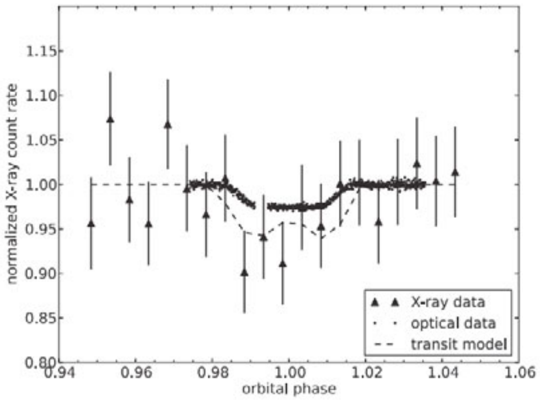
Knutson, et al. (2007), Nature, 447, 183.

Exoplanet Atmospheric Science − First Detection of Molecules in Exoplanet Atmosphere

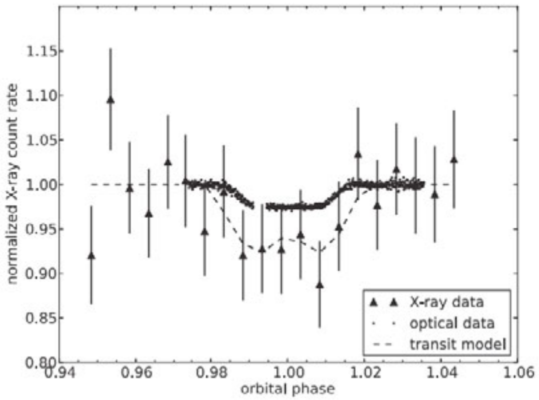


- HD 189733b
- Detection is in dayside spectrum, not a transit observation.
- Data − HST/NICMOS spectrograph
- Temperature decreases with altitude.
- An upper limit to methane is established.
- Resolution R~40

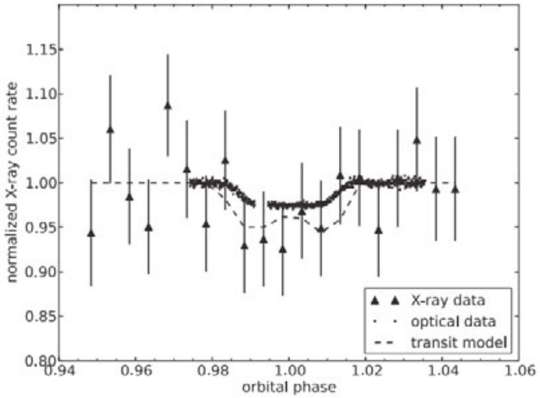
Swain, et al. (2009), ApJ, 690, 114.



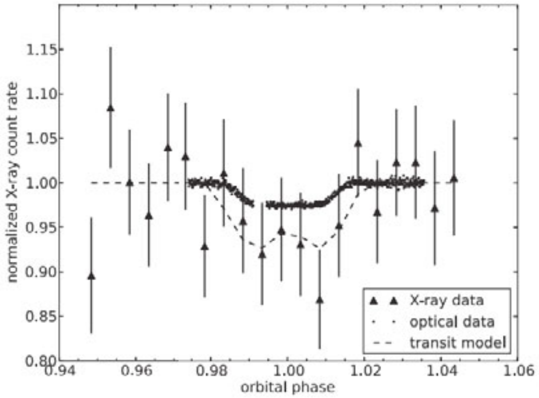
(a) All seven data sets



(b) Six data sets, excluding the potentially flaring *Chandra* observation



(c) Six data sets, excluding the potentially flaring *XMM-Newton* observation

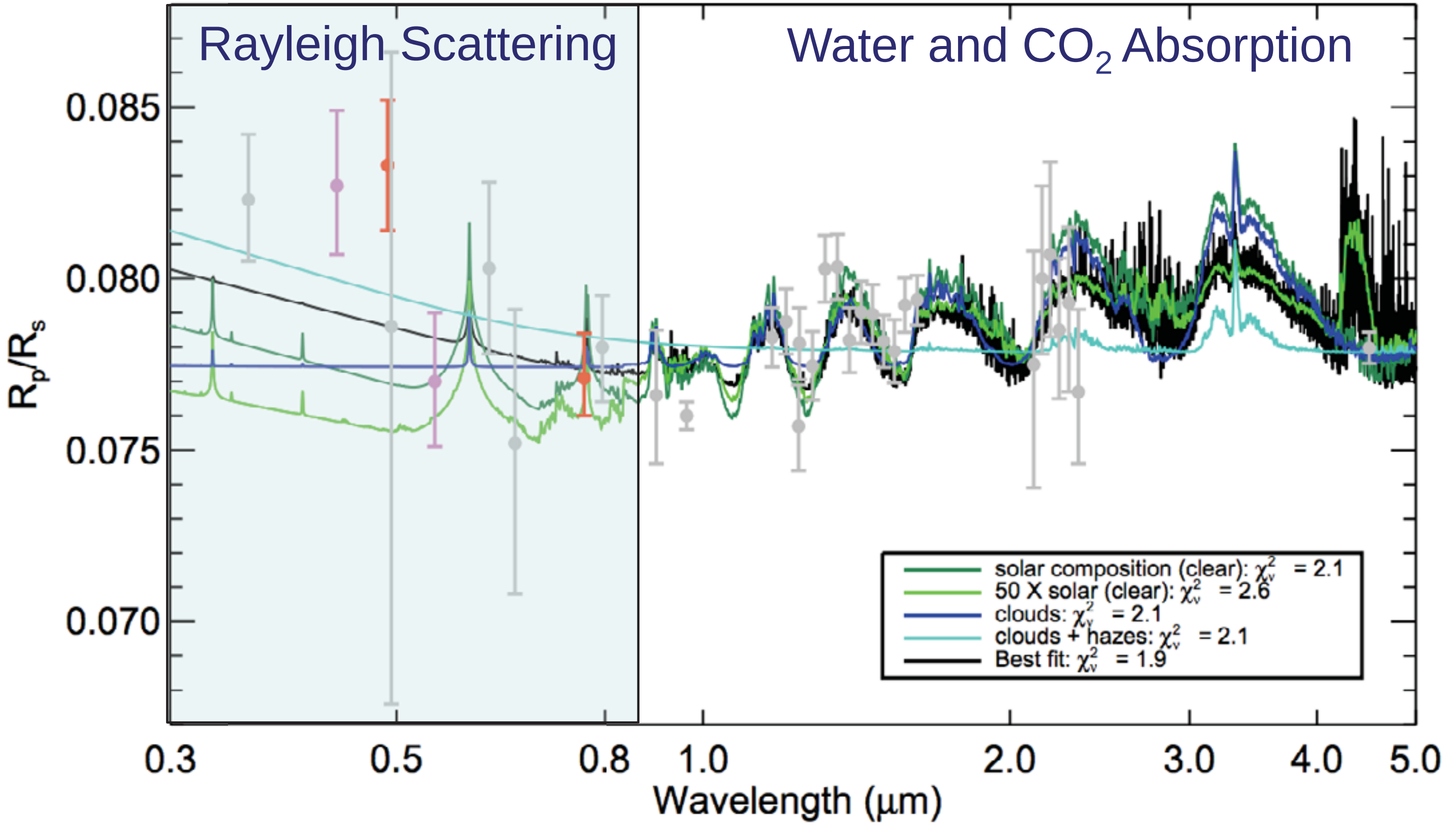


(d) Five quiescent data sets, excluding both potentially flaring observations

Figure 8. X-ray transit in comparison with optical transit data from Winn et al. (2007); vertical bars denote 1σ error bars of the X-ray data, dashed lines show the best fit to a limb-brightened transit model from Schlawin et al. (2010). The X-ray data are rebinned to phase bins of 0.005. The individual figures show different data combinations.

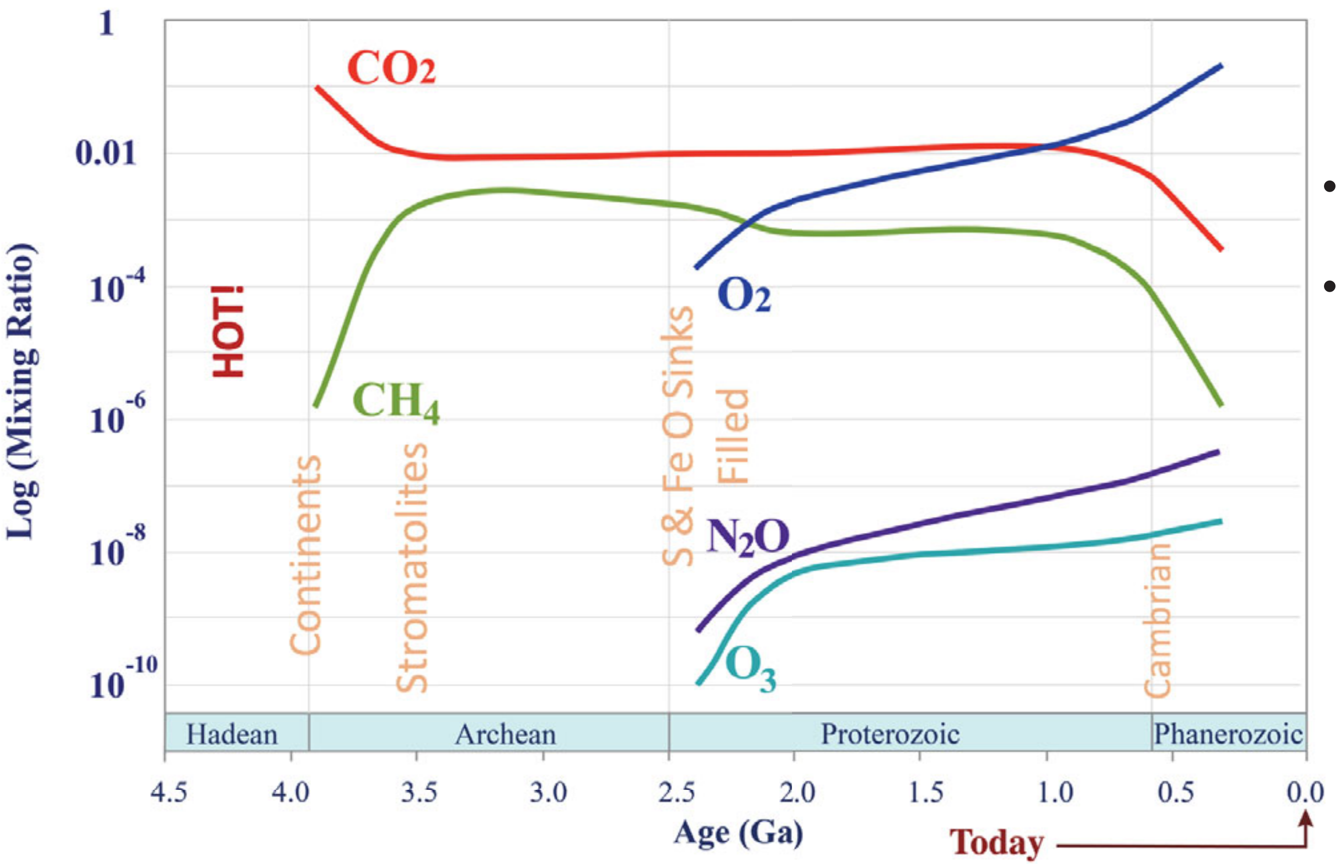
- Four transits observed with Chandra, one with XMM.
- Source is unresoved in XMM (?)
- Transit depth is 6-8%
- Optical (z-band) transit depth 2.41%.
- HD 189733b is “smaller” in the optical than in X-rays
- Evidence of an exosphere?

Poppenhager, Schmitt & Wolk, (2013), ApJ, 773, 62.



Dragomir et al. (2015), “Rayleigh Scattering in the Atmosphere of the Warm Exo-Neptune GJ 3470b”, arXiv:1511.05601

Oxygen as a Biomarker



- Biota accumulates during the Proterozoic (mostly bacteria).
- Biota "explodes" in the Cambrian, which marks the transition to the Phanerozoic
  - Abundant animal life becomes abundant.
  - Cambrian explosion enabled by Proterozoic oxygenization.

- Some atmospheric constituents are believed to be unique to planets that harbor life, especially oxygen (O_2)
- Detection of O_2 or ozone (O_3) would be extremely strong evidence of bioactivity on an exoplanet.

When Did Oxygen Become a Dominate Atmospheric Constituent?

The Economist | World politics | Business & finance | Economics | Science & technology | Culture

The ancient atmosphere

Time capsules

A new way to chart the rise of oxygen

Jul 30th 2016 | From the print edition   Timekeeper   Like 261   Tweet

OXYGEN makes up a fifth of the atmosphere (20.9%, to be precise), but that has not always been so. For the first 2 billion years of Earth's existence, before photosynthetic organisms became common, there was no chemically uncombined oxygen in the air at all. Even after that, the gas remained scarce for hundreds of millions of years. By 575m years ago, however—which was when animals whose dimensions are measured in centimetres rather than microns appear—there must have been enough oxygen around to support their respiration. The usual guess is that the gas's levels began to rise about 700m years ago. But a guess it is.

Economist Jul 30 2016

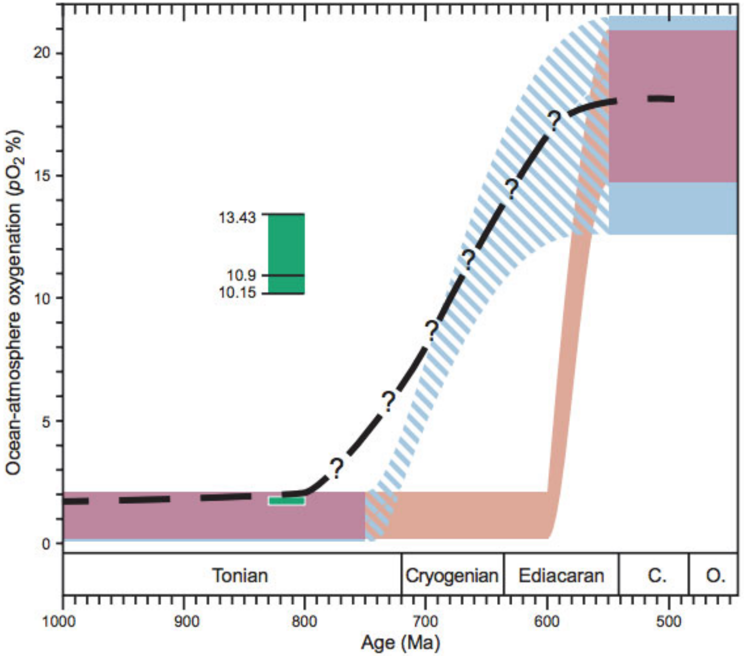
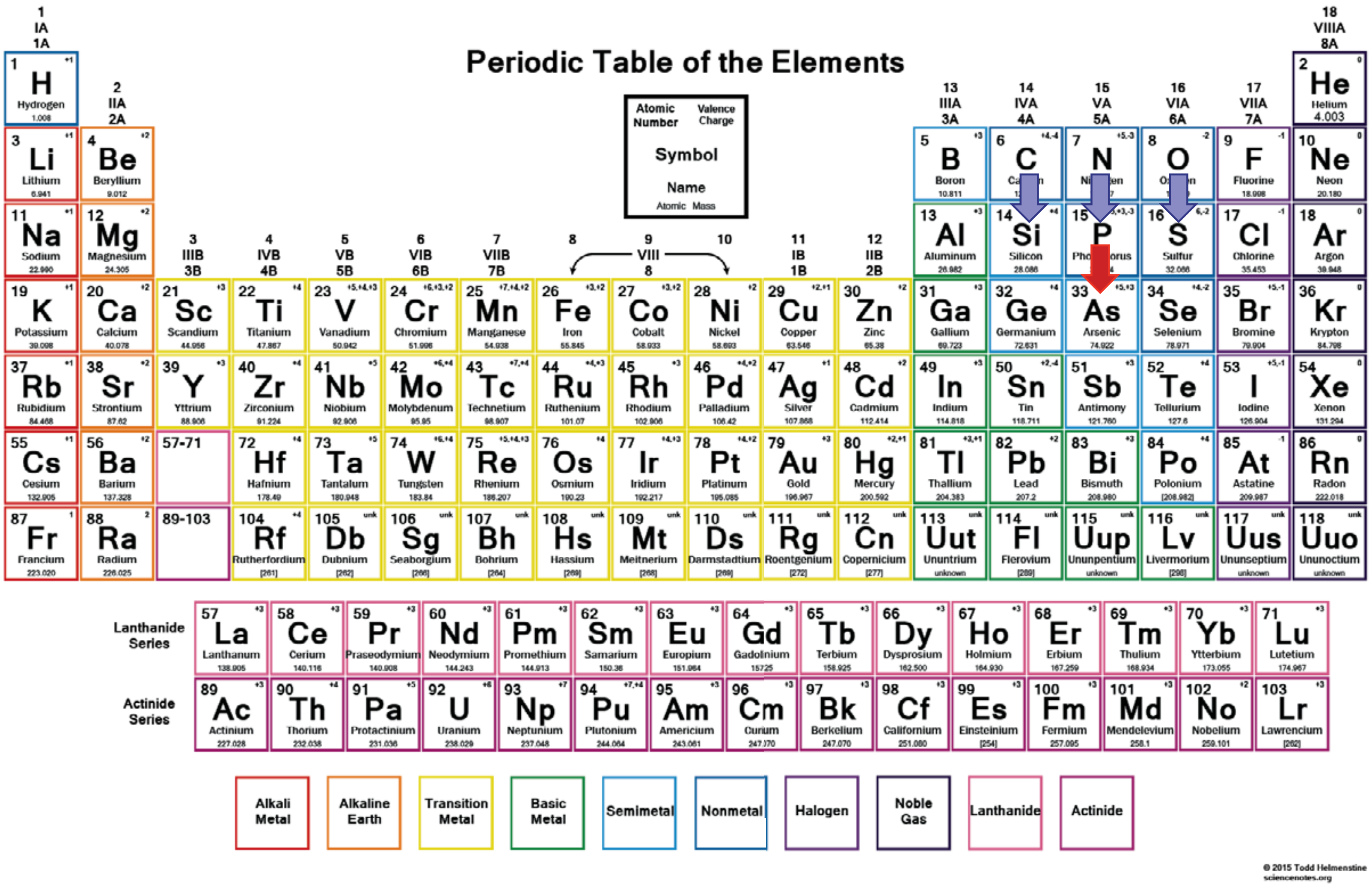
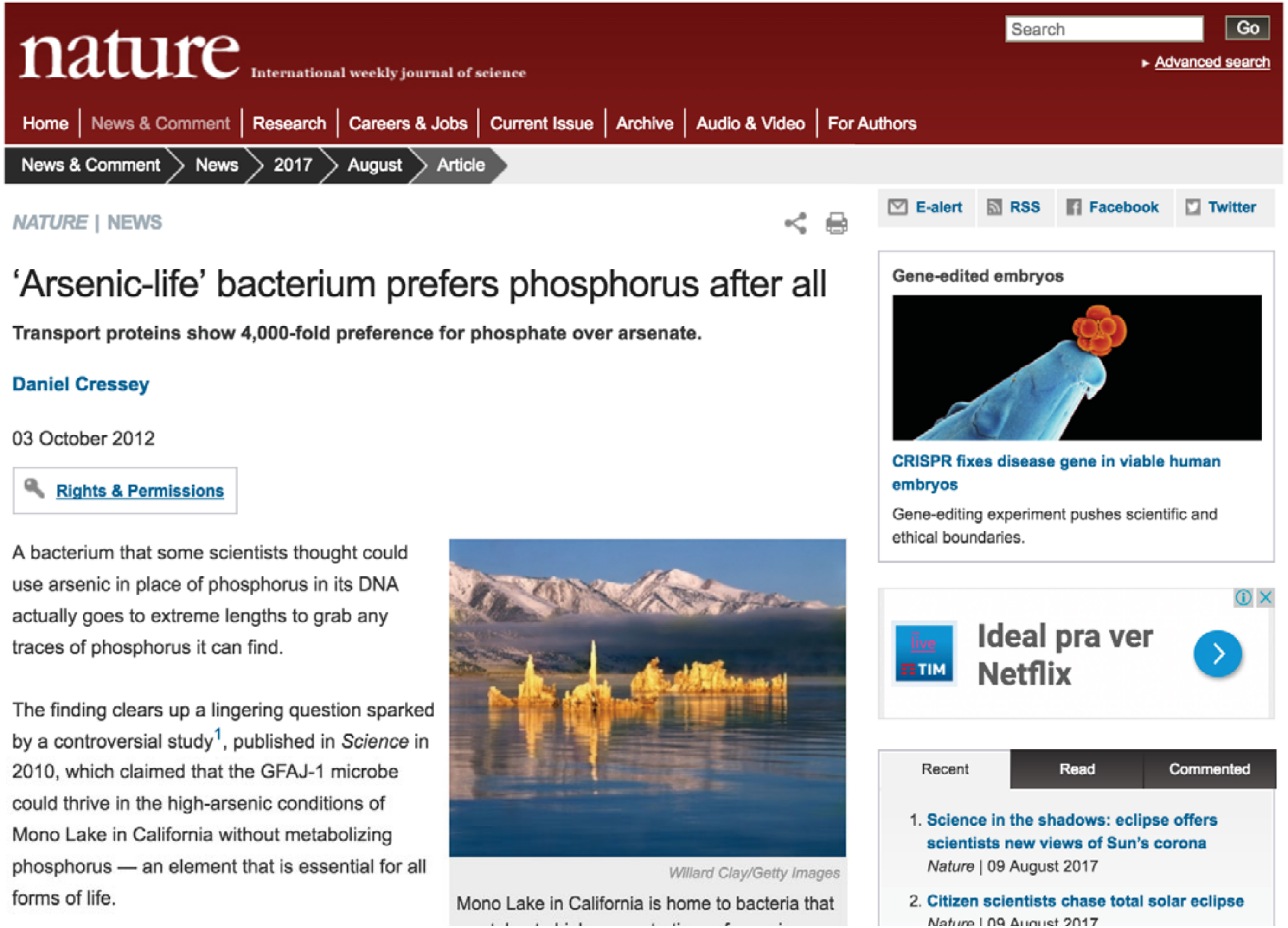


Figure 4. Atmosphere and ocean oxygenation trends during Neoproterozoic. Dashed line is proposed atmospheric oxygen trend by Canfield (2005), red unidirectional curve represents traditional viewpoint (e.g., Kump, 2008), and blue curve represents emerging model presented by Lyons et al. (2014). Green field shows our atmospheric oxygen measurements for Tonian time during Neoproterozoic (Table 1). C.—Cambrian; O.—Ordovician.

Now Universal is Carbon Based Life in Aqueoys Media?



Now Universal is Carbon Based Life in Aqueoys Media?



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'Arsenic-life' bacterium prefers phosphorus after all

Transport proteins show 4,000-fold preference for phosphate over arsenate.

Daniel Cressey

03 October 2012

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A bacterium that some scientists thought could use arsenic in place of phosphorus in its DNA actually goes to extreme lengths to grab any traces of phosphorus it can find.

The finding clears up a lingering question sparked by a controversial study[1], published in *Science* in 2010, which claimed that the GFAJ-1 microbe could thrive in the high-arsenic conditions of Mono Lake in California without metabolizing phosphorus — an element that is essential for all forms of life.

Willard Clay/Getty Images

Mono Lake in California is home to bacteria that

Gene-edited embryos

CRISPR fixes disease gene in viable human embryos

Gene-editing experiment pushes scientific and ethical boundaries.

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1. Science in the shadows: eclipse offers scientists new views of Sun's corona
Nature | 09 August 2017

2. Citizen scientists chase total solar eclipse
Nature | 09 August 2017

Scientists say NASA's 'new arsenic form of life' was untrue

July 9, 2012 by Kerry Sheridan

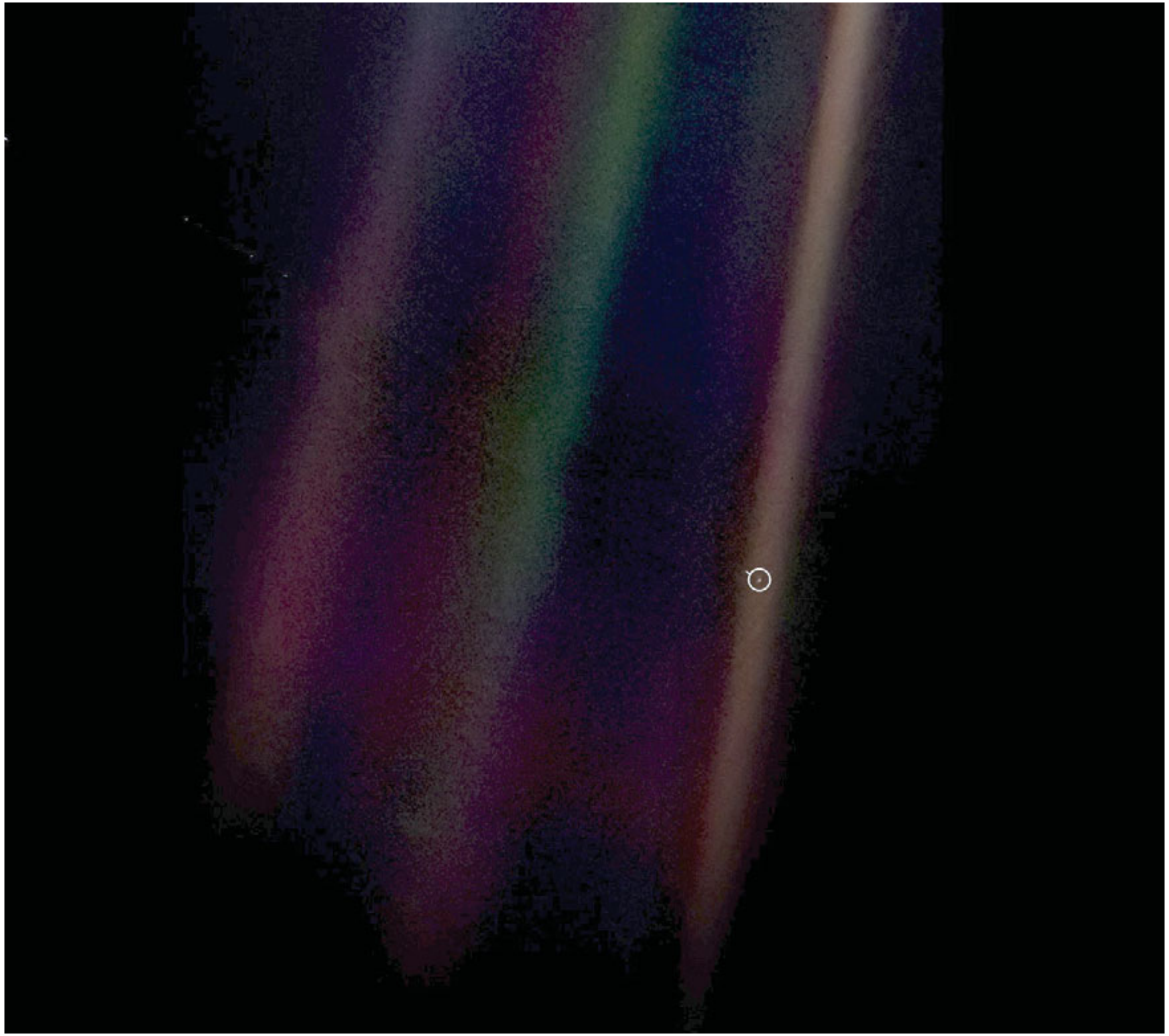
File photo of the Mono Lake in Lee Vining, California.

The original study needed to be confirmed in order to be considered a true discovery, and two separate teams found that indeed, the bacterium needed some phosphate to survive, and could not fully substitute arsenic to live.

NASA has conducted numerous probes at eastern California's Mono Lake, an unusually salty body of water with high arsenic and mineral levels, as it is likely to reflect conditions under which early life evolved on Earth, or perhaps Mars.

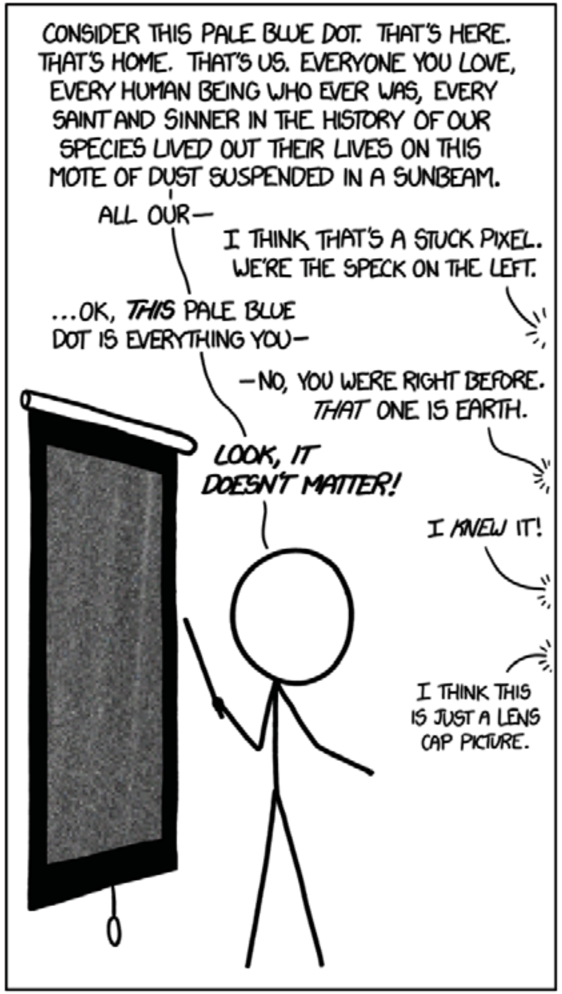
While Wolfe-Simon and colleagues acknowledged that there were very low levels of phosphate within their study samples, they concluded that this was a level of contamination that was insufficient to permit GFAJ to grow.

Two separate *Science* articles "now reveal that, in fact, her medium did contain enough phosphate contamination to support GFAJ-1's growth," said a statement by the magazine issued late Sunday.

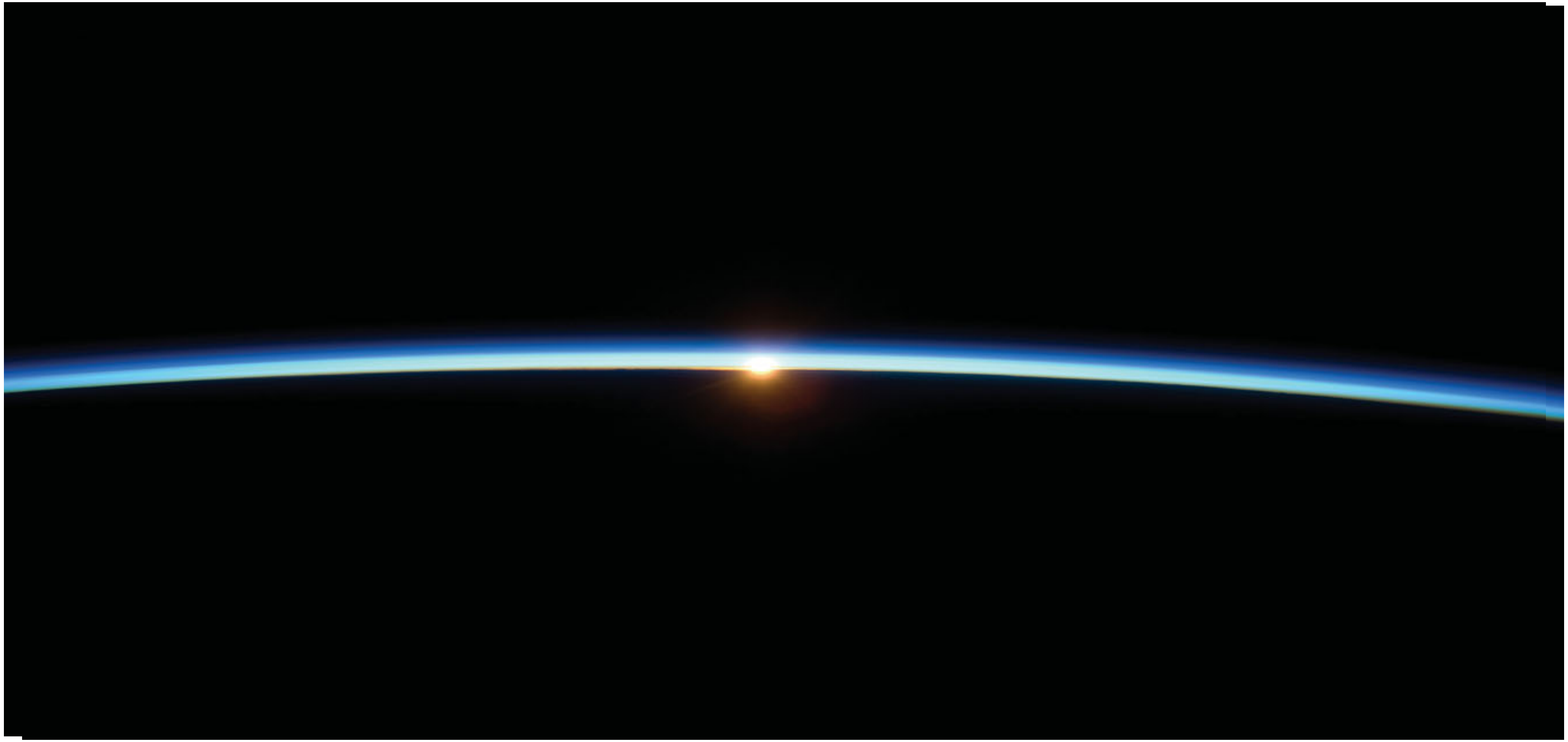


The Pale Blue Dot (1990)

- Taken from Voyager spacecraft at Carl Sagan's request.
- Distance was 6 billion miles.
- Multicolor photometry showed that the Earth was blue.
- Blue color was due to polarization and scattering.
- Polarization and scattering are due to clouds, exposed oceans, forests, etc.
- Generally evidence of a "hospitable", biotically active world.


CONSIDER THIS PALE BLUE DOT. THAT'S HERE. THAT'S HOME. THAT'S US. EVERYONE YOU LOVE, EVERY HUMAN BEING WHO EVER WAS, EVERY SAINT AND SINNER IN THE HISTORY OF OUR SPECIES LIVED OUT THEIR LIVES ON THIS MOTE OF DUST SUSPENDED IN A SUNBEAM.
ALL OUR—
I THINK THAT'S A STUCK PIXEL. WE'RE THE SPECK ON THE LEFT.
...OK, THIS PALE BLUE DOT IS EVERYTHING YOU—
—NO, YOU WERE RIGHT BEFORE. THAT ONE IS EARTH.
LOOK, IT DOESN'T MATTER!
I KNEW IT!
I THINK THIS IS JUST A LENS CAP PICTURE.


Green: [O] 5007Å
Red: [O] 6300Å



Earth's atmosphere seen from the dark side

Molecular O: O_2 is a major constituent of the Earth's atmosphere (21%)

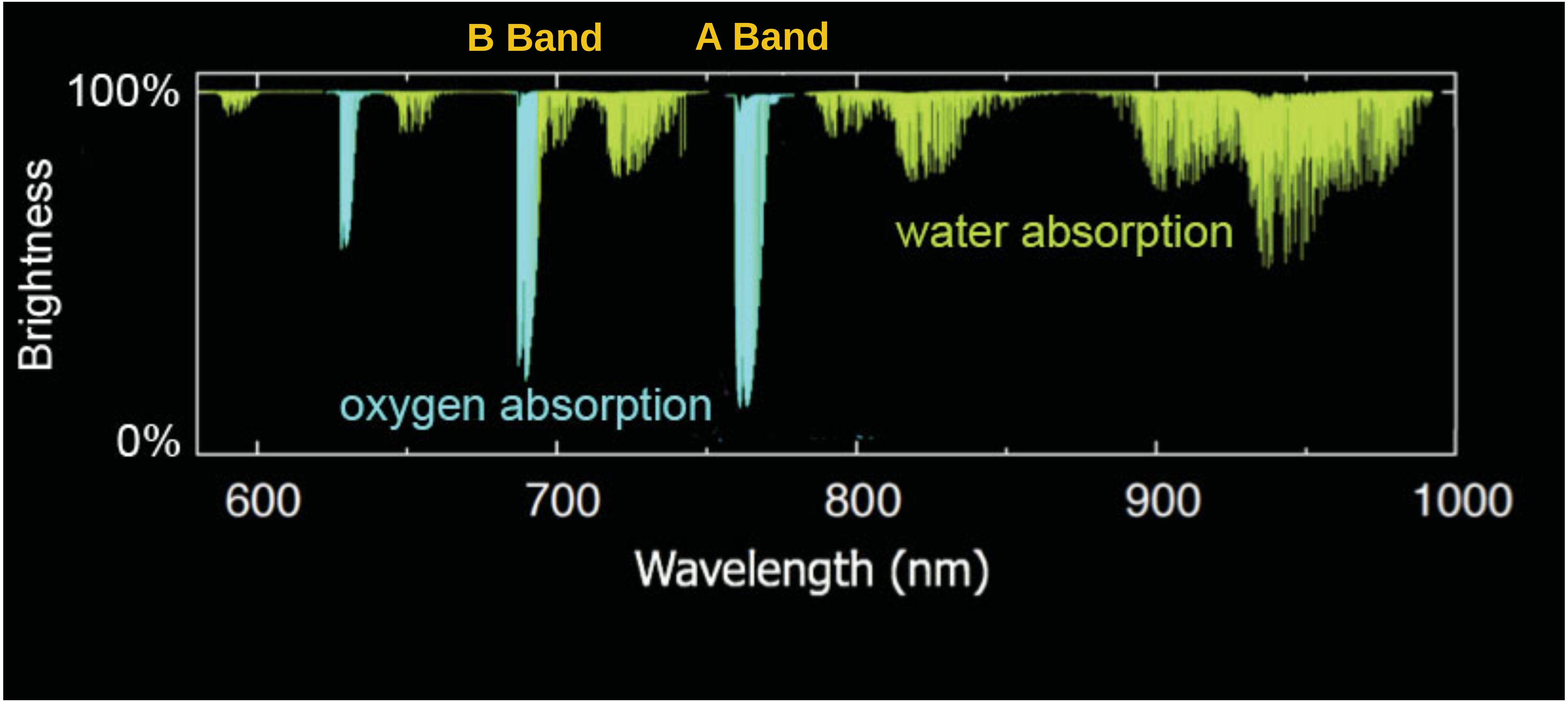
It is detectable 1% present in the 7600Å A-band or perhaps 0.1% in UV or thermal IR via O_3

CH_4: Is produced abiotically ~0.2 - 2% giant planets, ~5% Titan Water-rock H_2 can reduce CO_2 to abiotic CH_4.

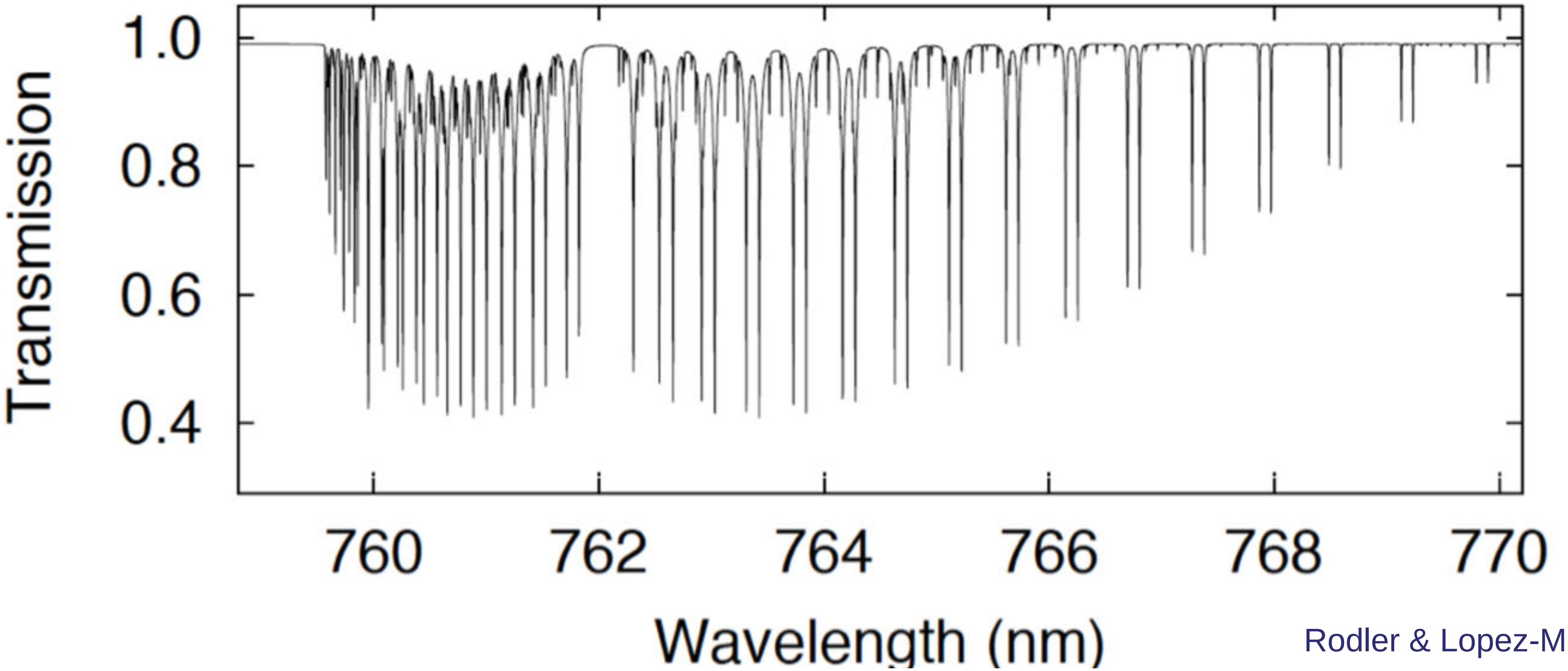
NH_3: Is produced abiotically e.g., Jupiter's upper clouds

N_2O: detection is difficult (~300 ppb on Earth)

$(CH_3)_2S$, CH_3Cl, CS_2, COS: are probably undetectable


B Band
A Band
100%
0%
Brightness
water absorption
oxygen absorption
600
700
800
900
1000
Wavelength (nm)

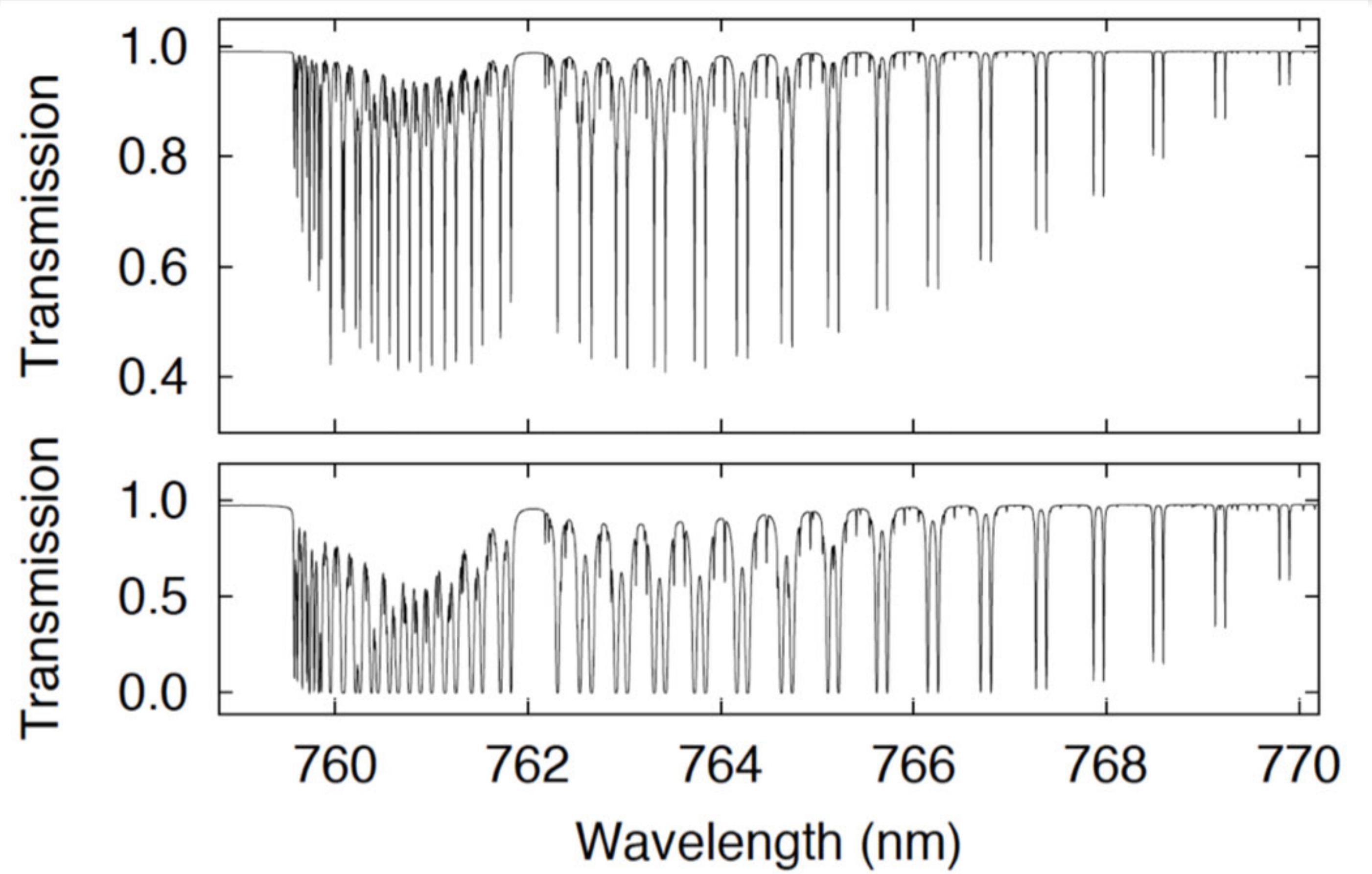
O_2 A-Band is a Easily Obervable Spectral Signature



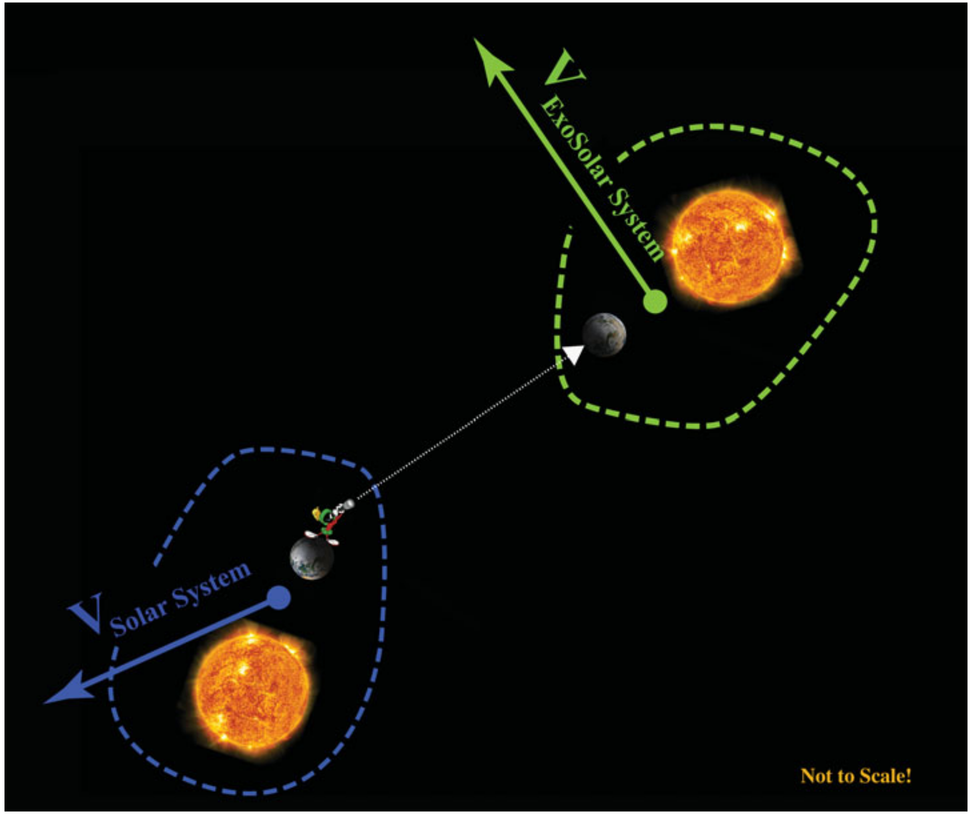
Rodler & Lopez-Morales, 2014.

- O_2 A-band spectrum of Earth-like planet.
- High resolution (R~ 100,000 − 5000,000) required to resolve molecular bandhead structure.

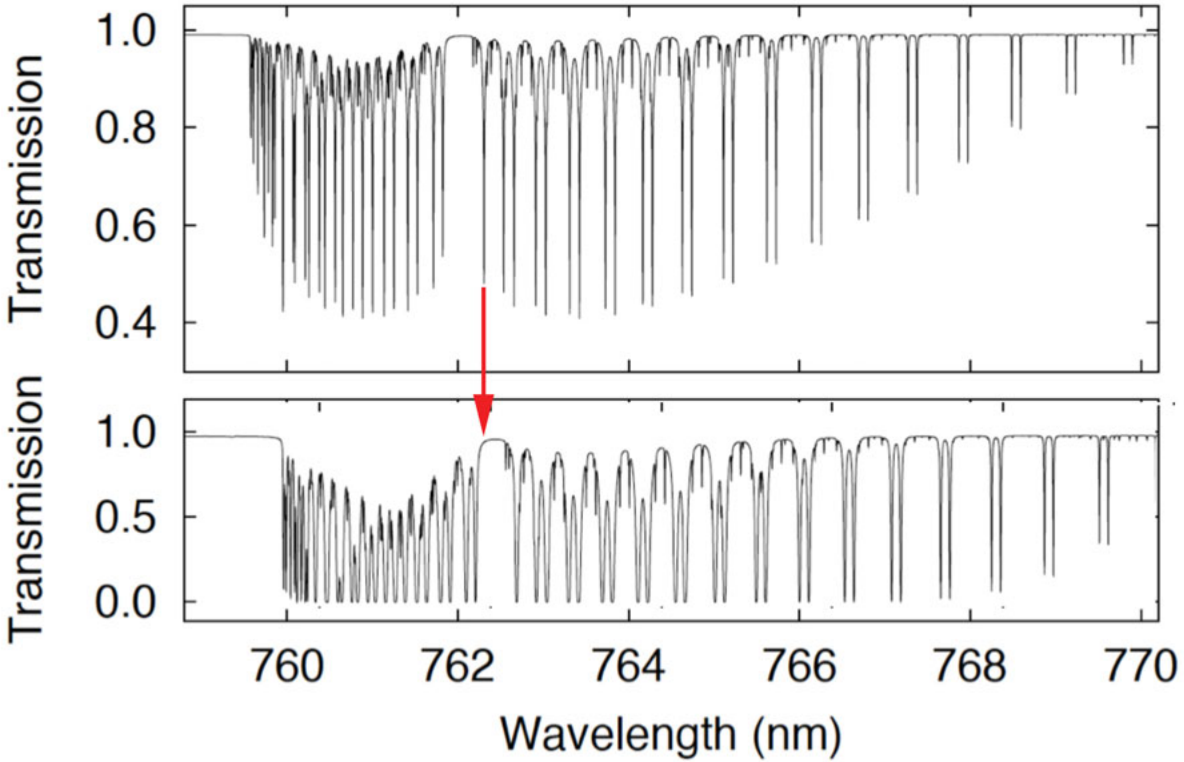
However, There is Strong Telluric Foreground Absorption



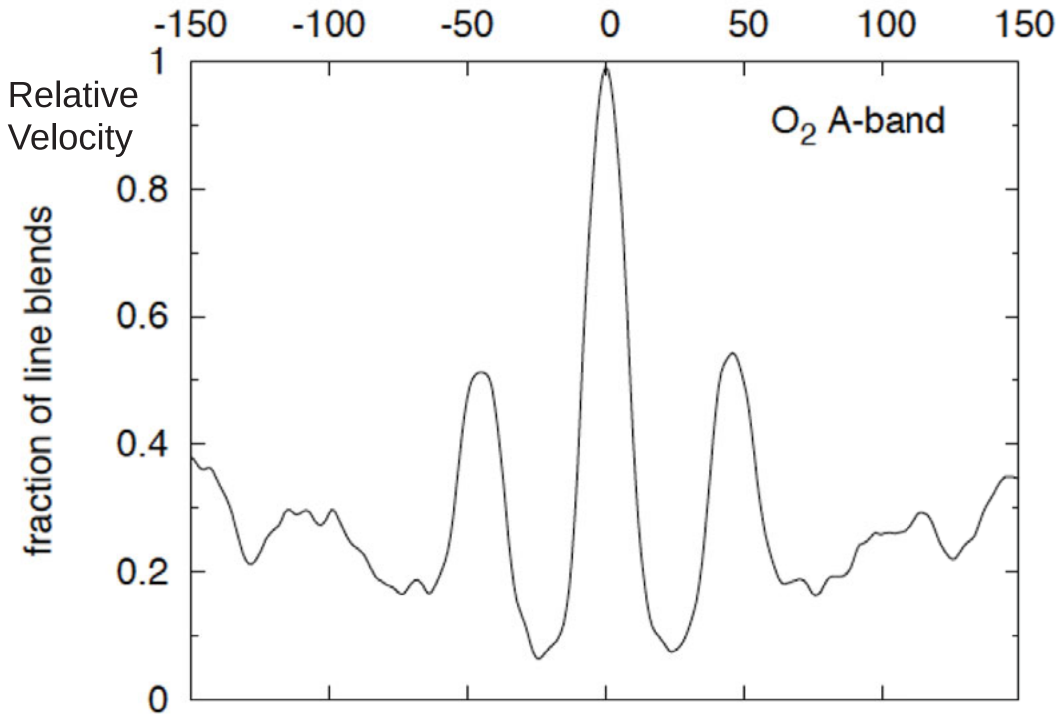
Top: O_2 A-band spectrum of Earth-like planet
Bottom: Telluric spectrum at Z=1.3 (30°off zenith)

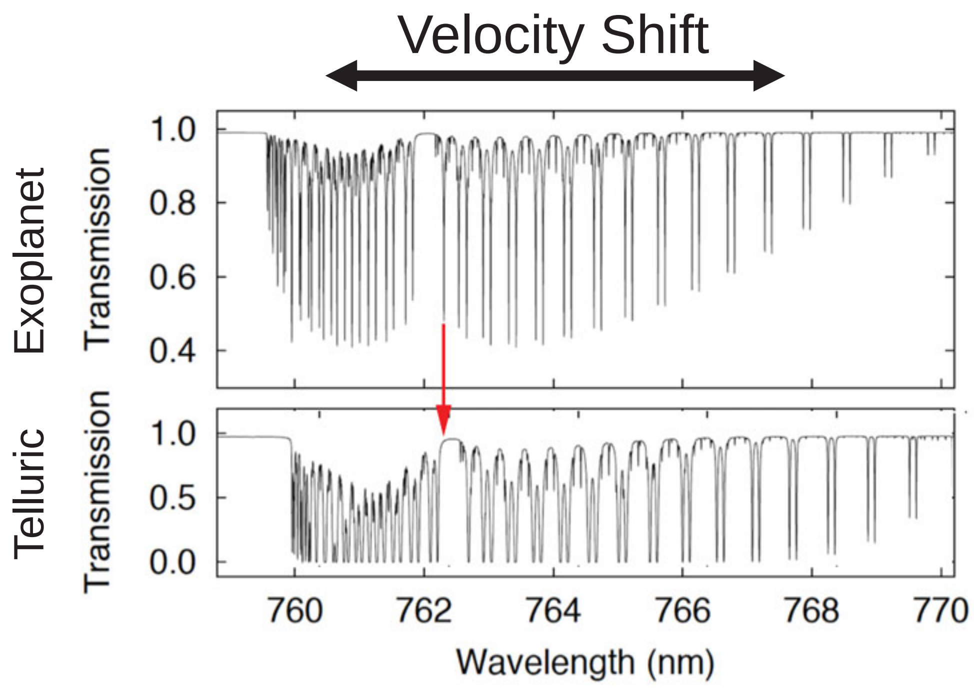


Line of sight velocity of exoplanet host star Doppler shifts intrinsic atmospheric absorption feature away from foreground, Telluric absorption



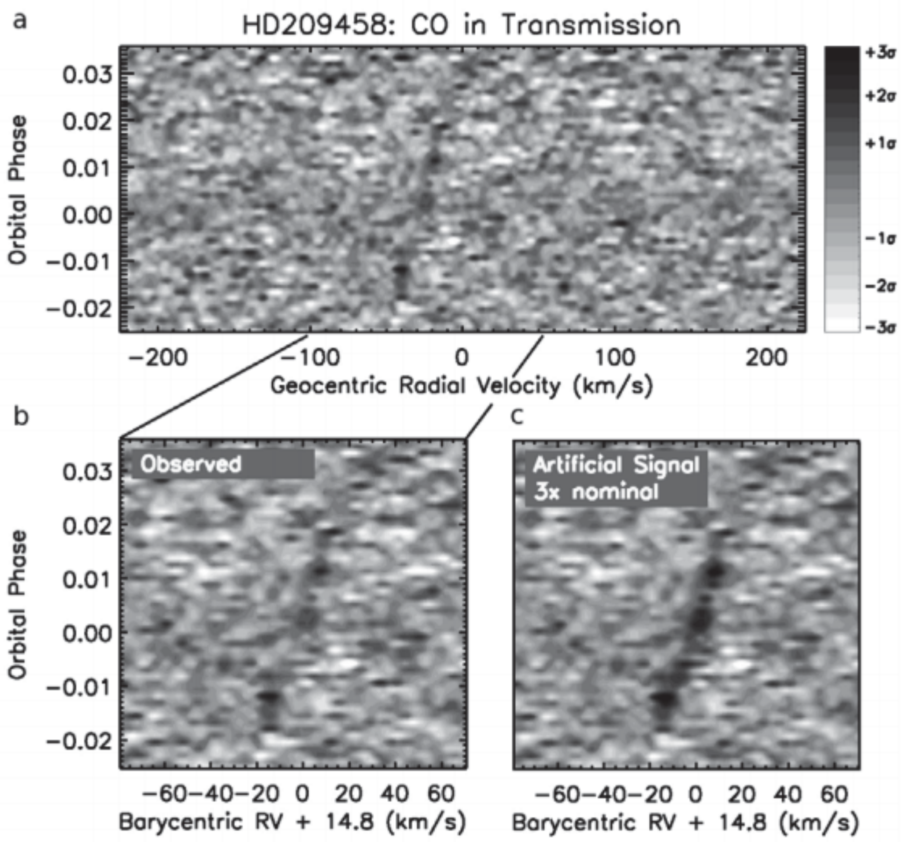
- Doppler shifting makes separation of Telluric and intrinsic absorption distinguishable.
- Telluric features calibrate instrinsic spectra; cross correlation improves detectability.





Some line of sight velocities will correlate intrinsic and Telluric absorption features, producing blends.

Proof of Principle Exists That Necessary Measurements Can Be Done



- Near Infrared spectra from CRIRES on VLT
- Planet is a hot Jupiter
- Absorption band of CO is clearly detected
- CO is blueshifted 2 km/sec

Snellen et al., 2010, Nature

Spectrograph Design for Natural Seeing

(Dan told you about spectrographs in the diffraction limit)

These slides leave out most intermediate calculations and details. These are written up in:

- Spectrographs_I.pdf
- Interferometers_I.pdf
- Fabry_Perot_Supplement.pdf

They are posted at:
https://drive.google.com/drive/folders/1BOE0WPn6mf_4kfKYqktEOkWsII4G6tVI
If you are having writing that address down, write me at:
saint@cfa.harvard.edu
and I will mail you the link.
Or get them from me on a thumb drive.

Example: The MMT

The MMT is a 6.5m, that can be operated in f/5 mode with the suitable secondary. In natural seeing (1") corresponds to:

$$1" \cdot F/\# \cdot D = 5 \times 10^{-6} \cdot 5 \cdot 6.5 = 150 \times 10^{-6} m = 150\,\mu$$

If, on the other hand, the telescope is corrected with adaptive optics, the telescope becomes (almost) diffraction limited and:

$$\phi_T \sim \frac{\lambda}{D_T} = \frac{0.5\,\mu}{6.5\,m} = 7.7 \times 10^{-8} Radians \sim 15\, milliarcsec$$

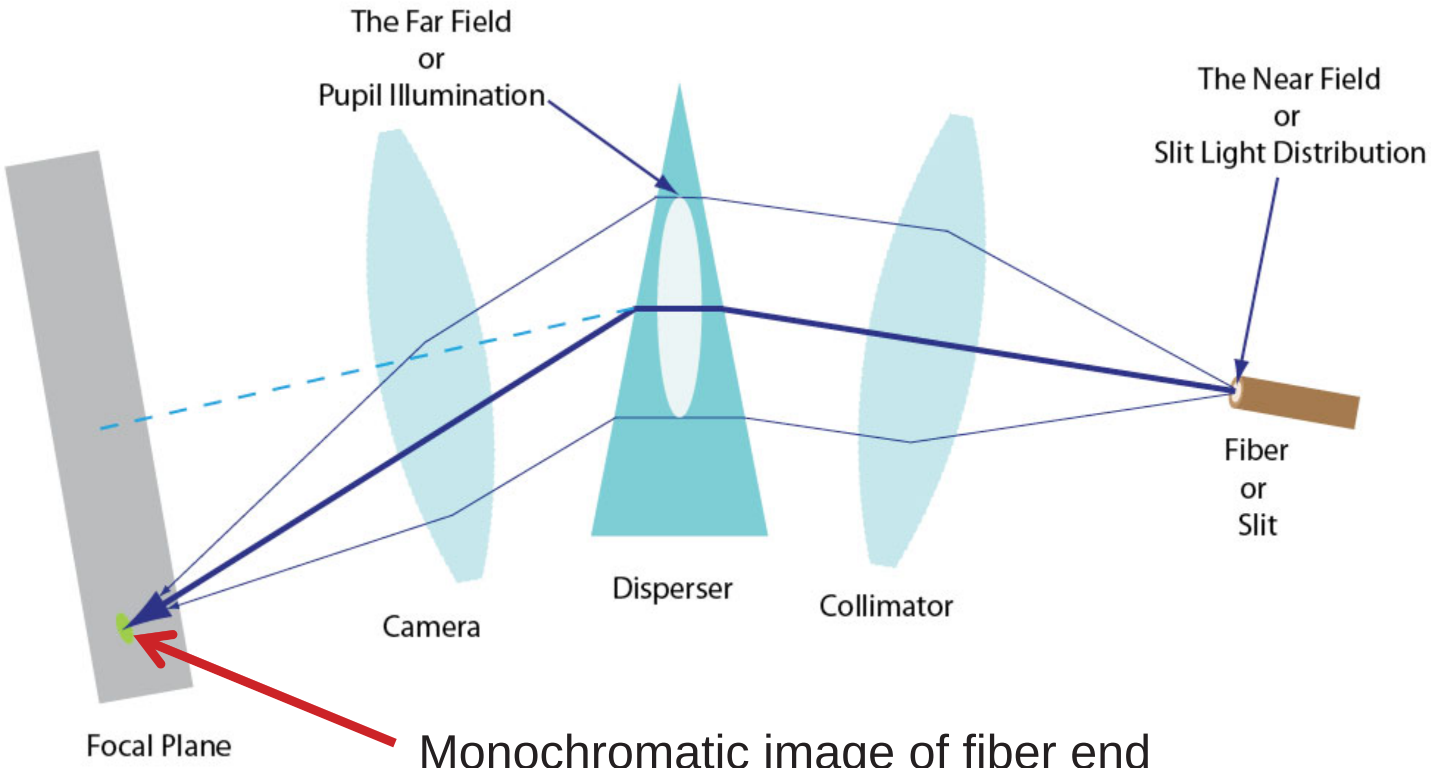
which corresponds to ~ 2.5 μ.

The slit size for a diffraction-limited instrument can be 60 time smaller than a spectrograph that operates in natural seeing.

- This means the instrument can be considerably smaller.
- Slit image is 60 ×smaller in equivalent spectrographs.
- Resolution ($R = \delta\lambda/\lambda$) is 60 ×higher in equivalent spectrographs.

A spectrograph produces monochromatic images of the input or slit on the focal plane of the spectrograph detector.

- The illumination pattern at the slit is often called the “near field”.
- The illumination pattern in the collimator beam is often called the “far field”.



Determinants of a Spectrograph Design

There are three physical factors that determine a spectrograph design, i.e. set the scale for a spectrograph:

1. The size of the seeing disk.
2. The size of the pixel of the detector.
3. The invariance of the AΩ product.

The design is further shaped by:

4. The science objectives of the instrument, principally through the maximum required resolution.
5. The desire to maximize the throughput or efficiency of the spectrograph.

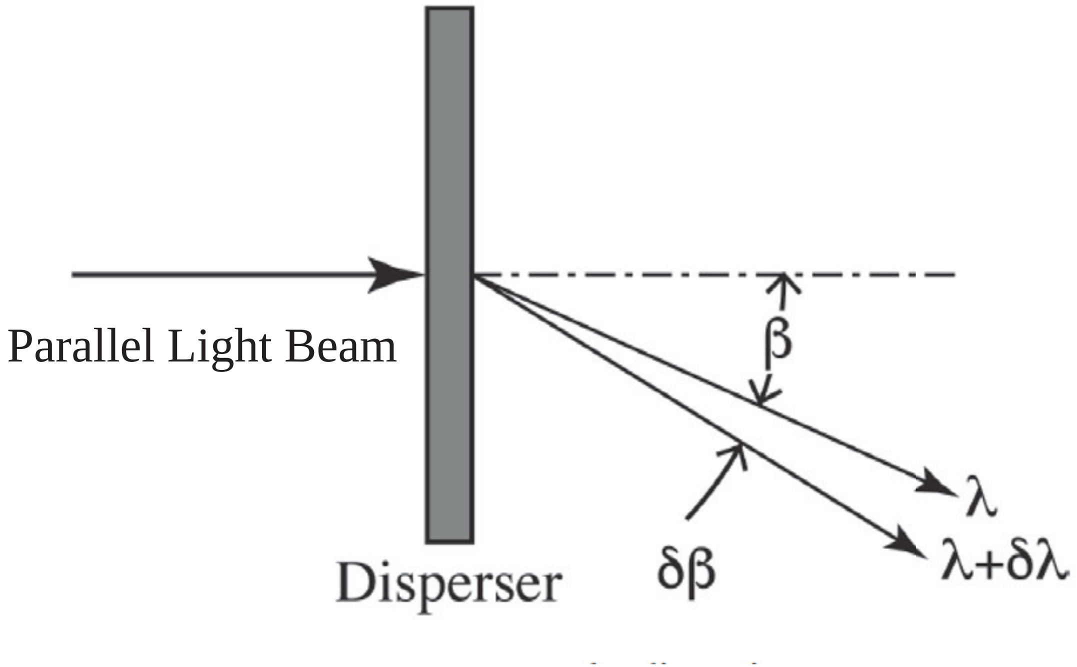
- Natural seeing: 0.6 arcsec
- Seeing with adaptive optics correction: 10 milliarcsec.

A sampling of resolutions and science objectives:

Science Objective	Required Resolution	Comments
Galactic Redshift	> 1000	Optical passband
Galactic Redshift	> 3000	NIR passband, for Telluric OH rejection
YSO Accretion	4000	
Star Cluster Membership	5000 – 7000	
Stellar Abundance	40,000	
Isotope Shift	60,000	
Lyα Forest Studies	100,000	
Exoplanet Detection	110,000	Precision radial velocity of FGK stars
Search for Biomarkers	110,000 – 300,000	O_2 A-band in exoplanet atmospheres

The science objective is the independent parameter.
The resolution is dependent variable.
The solution has boundary conditions – allowable mass, budget, &c.

Angular Dispersion in a Very Simple Spectrograph



$$\frac{d\beta}{d\lambda}$$

Linear Dispersion in a Simple Spectrograph

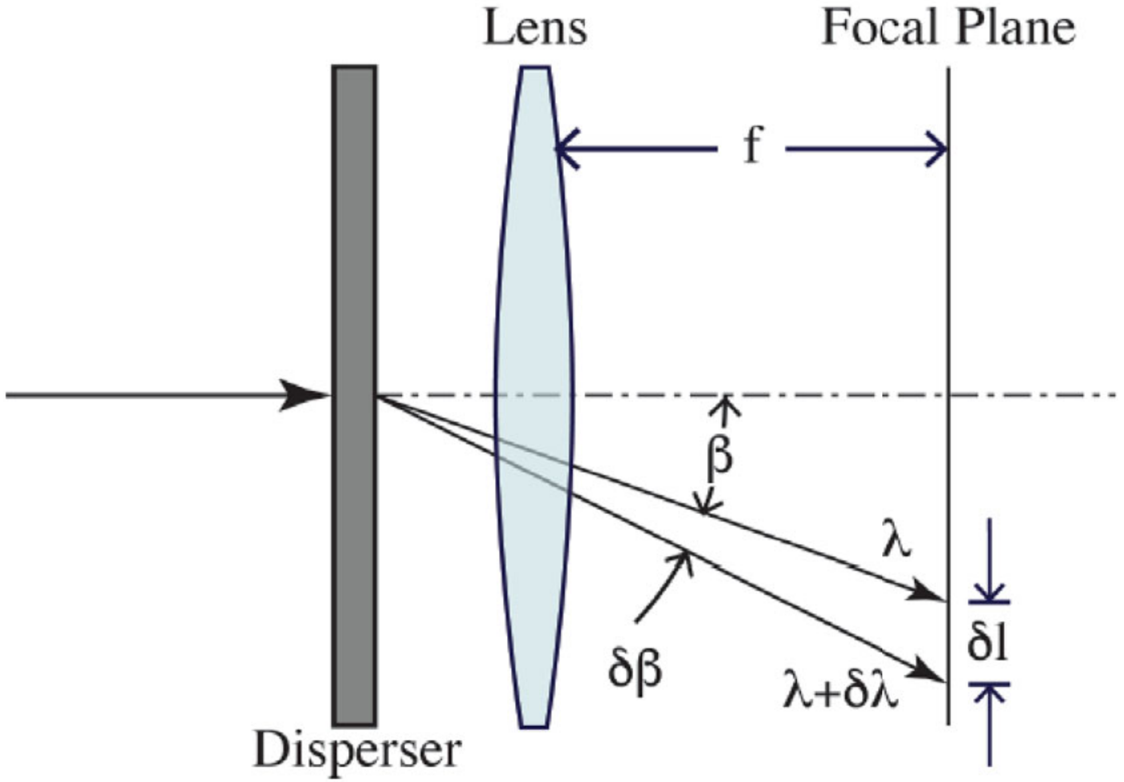
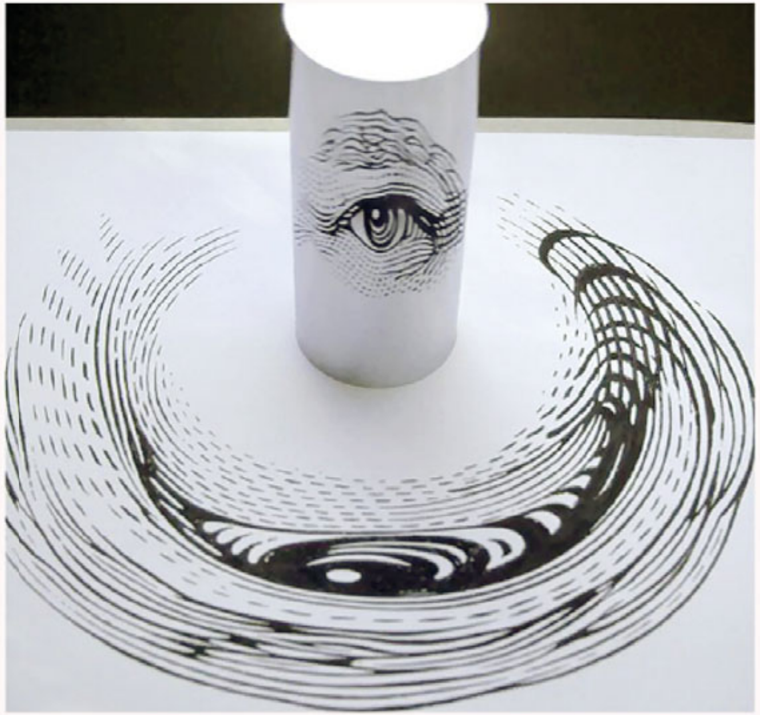


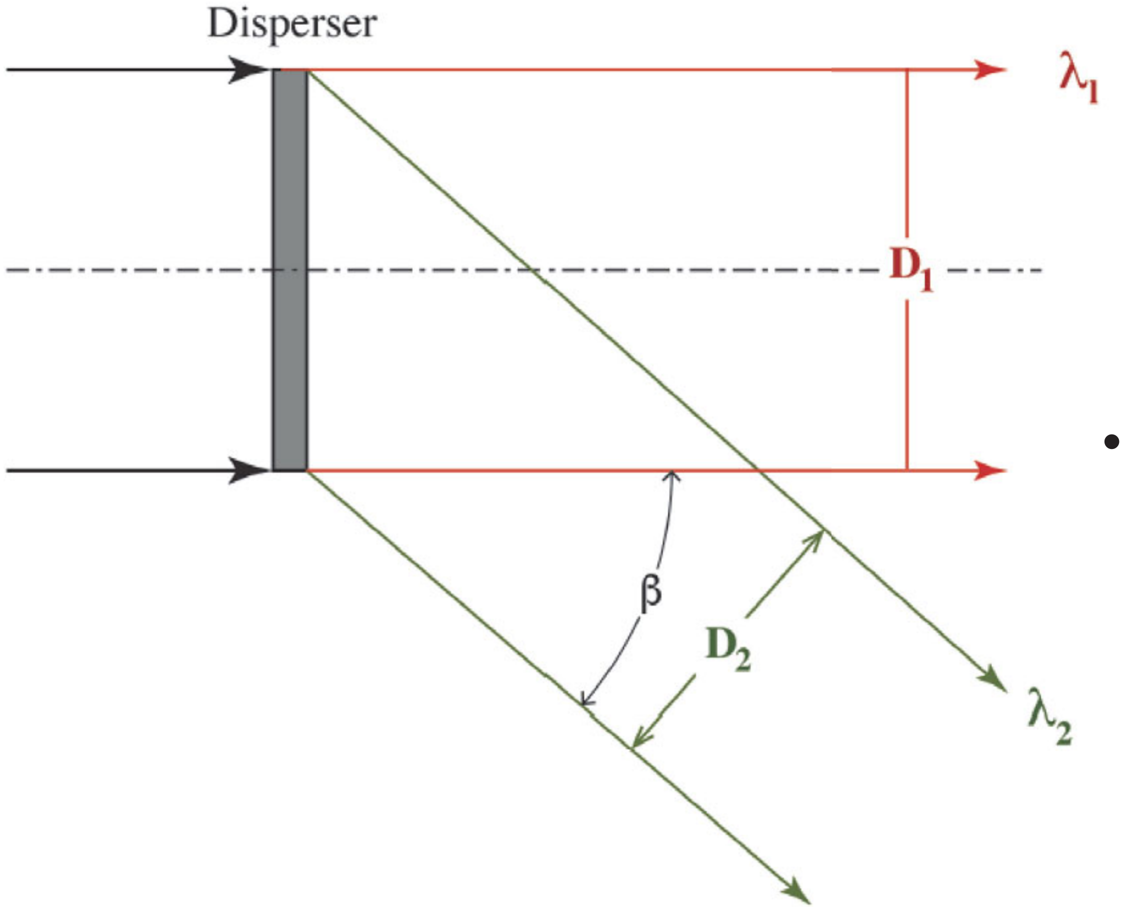
Figure 2: Linear dispersion

$$\frac{dl}{d\lambda} = f_c \times \frac{d\beta}{d\lambda}$$

Anamorphism in action



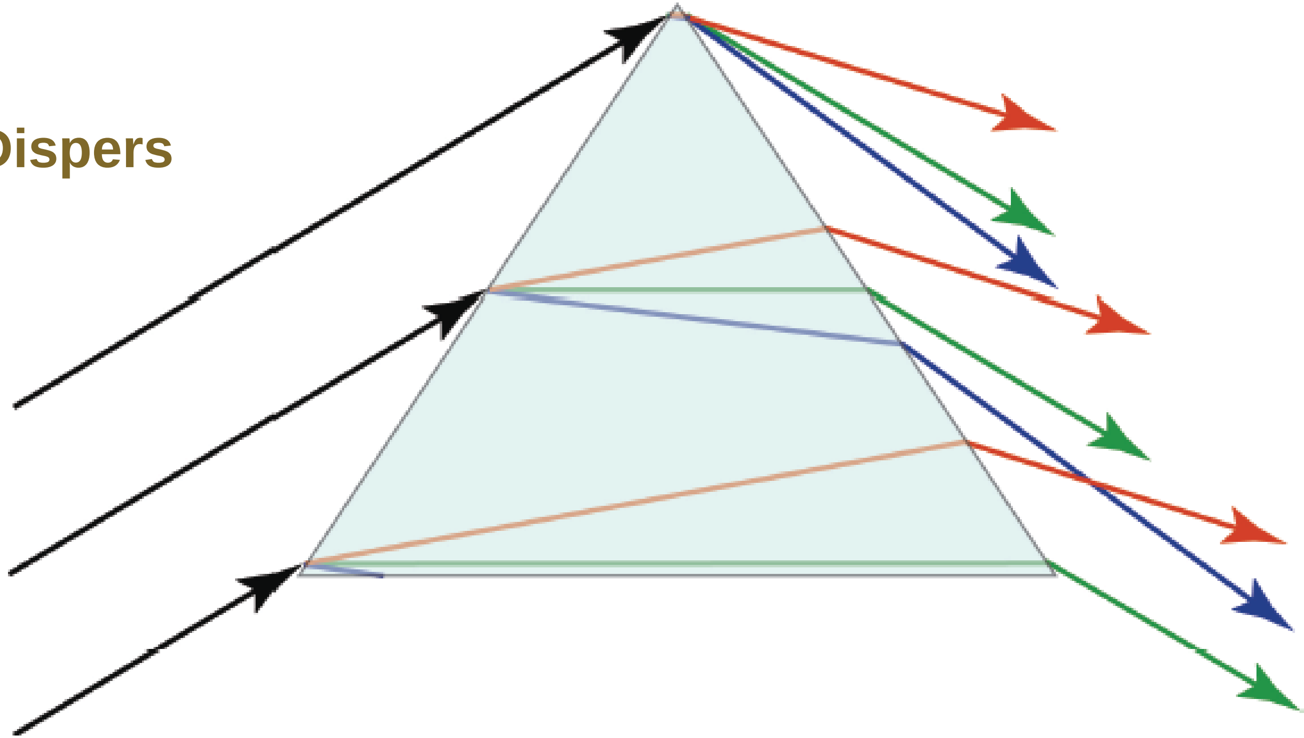
Anamorphic Factor



$$r = \text{Cos}(\beta)$$

- Anamorphism distorts the shape of the slit image.

Prisms as Dispers



1. As is seem in Figure 8, there is some loss of light at the bottom of the prism for wavelengths bluer than the minimum deviation wavelength.
2. For all "sensible" angles of incidence and refraction, the angle of refraction is always pretty close to minimum deviations, since the all functions are relatively flat near minima, where the slope is zero.

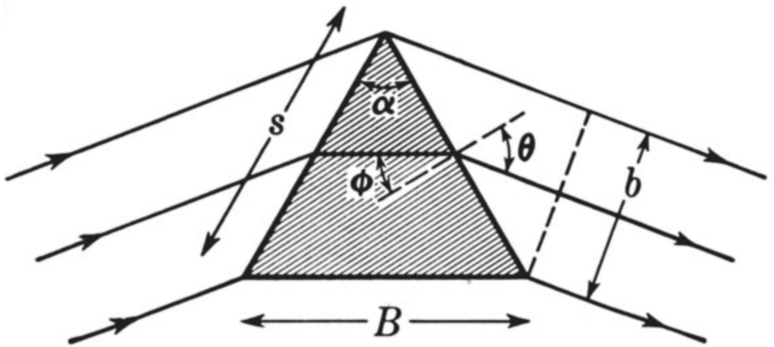


FIG. 23A. Refraction by a prism at minimum deviation.

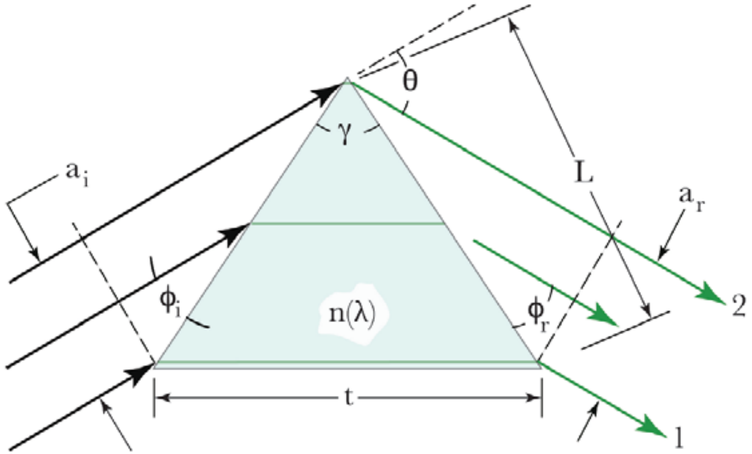
Prism Spectrographs - Dispersion Considerations

$$\frac{d\theta}{d\lambda} = \frac{B}{b}\frac{dn}{d\lambda}$$

Wave-length, λ, in Å	Telescope crown		Borosilicate crown		Barium flint		Vitreous quartz	
	n	$-\frac{dn}{d\lambda}$	n	$-\frac{dn}{d\lambda}$	n	$-\frac{dn}{d\lambda}$	n	$-\frac{dn}{d\lambda}$
C 6563	1.52441	0.35×10^{-5}	1.50883	0.31×10^{-5}	1.58848	0.38×10^{-5}	1.45640	0.27×10^{-5}
6439	1.52490	0.36×10^{-5}	1.50917	0.32×10^{-5}	1.58896	0.39×10^{-5}	1.45674	0.28×10^{-5}
D 5890	1.52704	0.43×10^{-5}	1.51124	0.41×10^{-5}	1.59144	0.50×10^{-5}	1.45845	0.35×10^{-5}
5338	1.52989	0.58×10^{-5}	1.51386	0.55×10^{-5}	1.59463	0.68×10^{-5}	1.46067	0.45×10^{-5}
5086	1.53146	0.66×10^{-5}	1.51534	0.63×10^{-5}	1.59644	0.78×10^{-5}	1.46191	0.52×10^{-5}
F 4861	1.53303	0.78×10^{-5}	1.51690	0.72×10^{-5}	1.59825	0.89×10^{-5}	1.46318	0.60×10^{-5}
G′ 4340	1.53790	1.12×10^{-5}	1.52136	1.00×10^{-5}	1.60367	1.23×10^{-5}	1.46690	0.84×10^{-5}
H 3988	1.54245	1.39×10^{-5}	1.52546	1.26×10^{-5}	1.60870	1.72×10^{-5}	1.47030	1.12×10^{-5}

The geometry of a prism spectrograph

Variable	Quantity
L	Length of the side of a prism.
t	Length of the base of the prism
a_i, a_r	Size of beam in the plane of refraction before and after refraction (i & r)
γ	Prism apex angle
ϕ_i, ϕ_r	Angle of incidence and refraction
θ	Angle of deviation
λ	Wavelength of beam
n(λ)	Index of refraction at wavelength λ



$$\frac{d\beta}{d\lambda} = \frac{t}{a} \cdot \frac{dn}{d\lambda} = \frac{-2t}{a} \cdot \frac{B}{\lambda^3}$$

$$n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} + \cdots \approx A + \frac{B}{\lambda^2}$$

$$\frac{d\beta}{d\lambda} = -2 \cdot \left\{\frac{\pi}{2} - \mathrm{Sin}^{-1}\left\{n \cdot \mathrm{Sin}\left(\frac{\gamma}{2}\right)\right\}\right\} \cdot \frac{B}{\lambda^3}$$

Need a lookup table for B

Table 3: Table coefficients of a range of glasses for calculating index of refraction by the Cauchy equation. n_0 is the zero order index of refraction. Both Schott and Ohara designators are listed. These are all frequently melted glasses, except for N-K5 (S-NSL5). ϕ and $\frac{d\beta}{d\lambda}$ are calculated for a prism with a 30° apex angle.

Glass Schott (Ohara)	A (n_0)	B (μm^2)	Type	ϕ	$\frac{d\beta}{d\lambda}$ (μm^{-1})
Fused Silica	1.4580	0.00354		67.830	-3.24×10^{-2}
N-BK7 (S-BSL7)	1.5046	0.00420	Borosilicate	67.082	-3.80×10^{-2}
N-K5 (S-NSL5)	1.5220	0.00459	Hard crown	66.801	-4.14×10^{-2}
N-BaK4 (S-BAL14)	1.5690	0.00531	Barium crown	66.041	-4.73×10^{-2}
N-BaF10 (S-BAH10)	1.6700	0.00743	Barium flint	64.391	-6.45×10^{-2}
N-SF10 (S-TIH10)	1.7280	0.01342	Dense flint	63.433	-1.15×10^{-1}

The ultimate resolution of a prism spectrograph

$R=\lambda/\delta\lambda$

$$\delta\lambda_0 = \frac{dl}{\left(f_{Cam}\cdot\frac{d\beta}{d\lambda}\right)} = \frac{w'}{\left(f_{Cam}\cdot\frac{d\beta}{d\lambda}\right)} = \frac{\lambda\cdot F_{Cam}}{\left(f_{Cam}\cdot\frac{d\beta}{d\lambda}\right)} = \frac{\lambda}{\left(D_{Cam}\cdot\frac{d\beta}{d\lambda}\right)}$$

$$\frac{d\beta}{d\lambda} = -2\cdot\left\{\frac{\pi}{2} - \mathrm{Sin}^{-1}\left\{n\cdot \mathrm{Sin}\left(\frac{\gamma}{2}\right)\right\}\right\}\cdot\frac{B}{\lambda^3}$$

So, for a 100 mm camera aperture with a N-SF10 prism with a 30°apex angle (see Table 3., previous slide), in the diffraction limit the maximum achievabel resolution is: 100,000 × 1.15 ×10^{-1} ~ 11,000. Note very high − insufficient for most astrophysical spectroscopy. Another disperser technology is needed.

Heroic instrumentation efforts of the past.

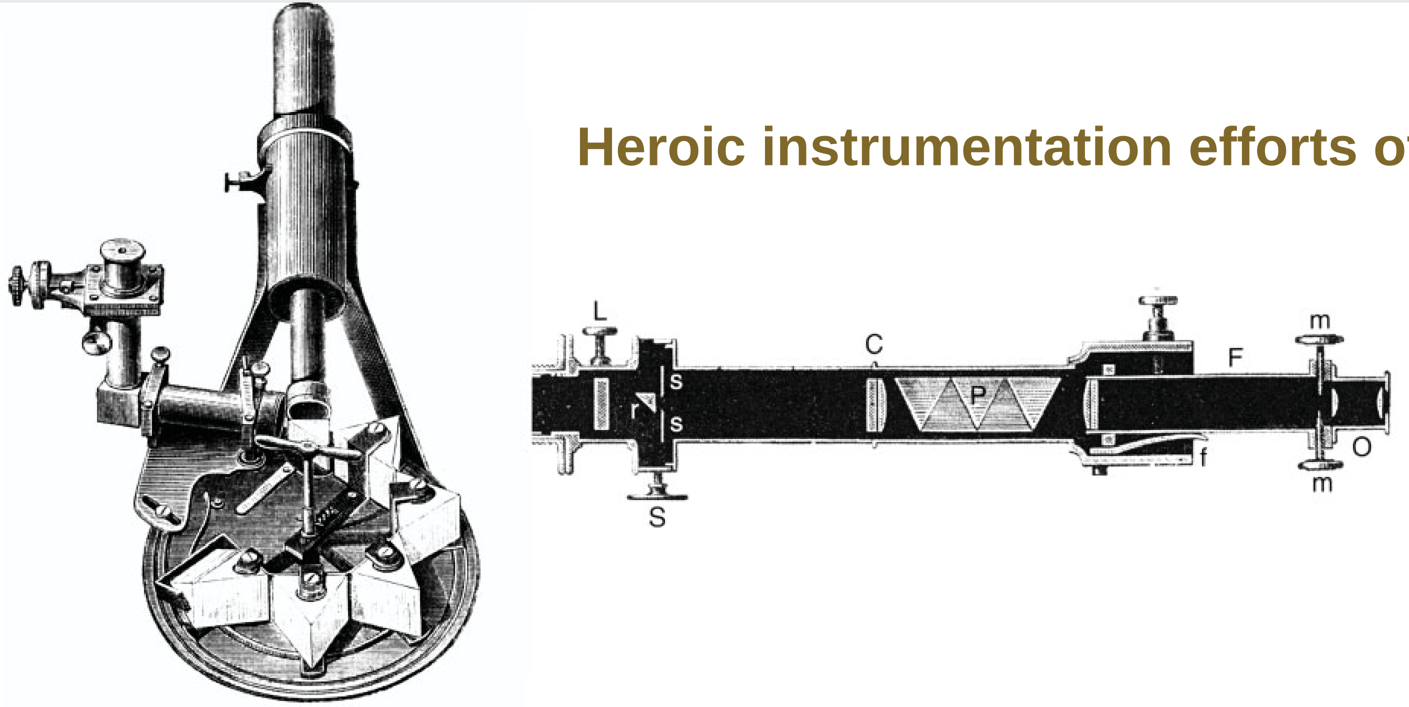


Figure 10: Left Panel: Angelo Secchi's automatic double-pass spectrograph, circa 1870. The first prism reflects the light into the lower half od the prism train, it returns through the upper half into the viewing telescope to the left. Right Panel: Angelo Secchi direct viewing spectrograph with 5 oiled or bonded prisms, circa 1862. This tiny prism at r made it possible to introduce a comparison spectrum (from Hearnshaw, 2009).

12 prism passages reduce efficiency drastically!

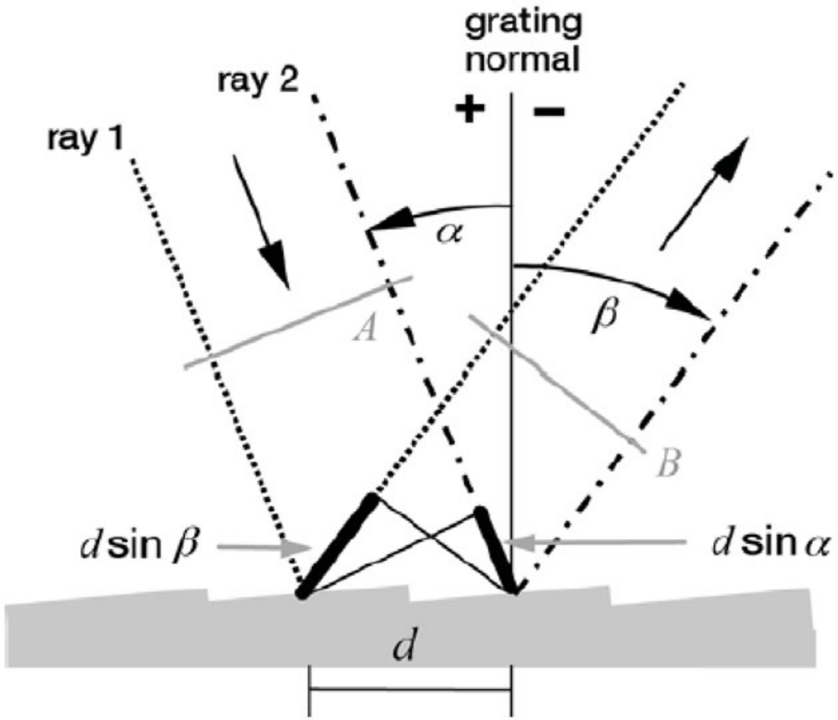


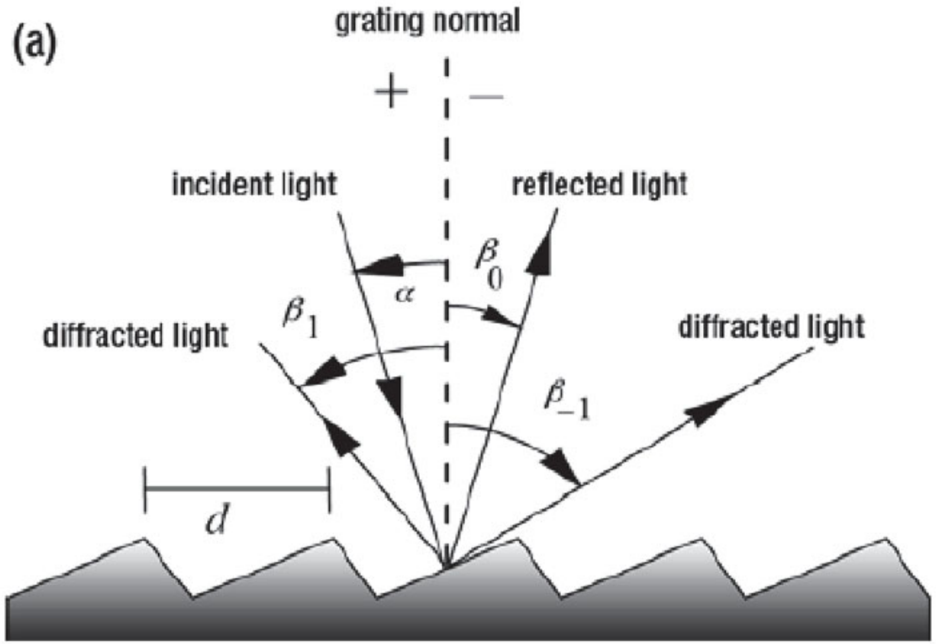
Figure 2-2. Geometry of diffraction, for planar wavefronts. Two parallel rays, labeled *1* and *2*, are incident on the grating one groove spacing *d* apart and are in phase with each other at wavefront *A*. Upon diffraction, the principle of constructive interference implies that these rays are in phase at diffracted wavefront *B* if the difference in their path lengths, $d\sin\alpha + d\sin\beta$, is an integral number of wavelengths; this in turn leads to the grating equation.

The Diffraction Grating

The grating equation:

$$\pm m\lambda = d\,\{\sin\alpha \pm \sin\beta\}$$

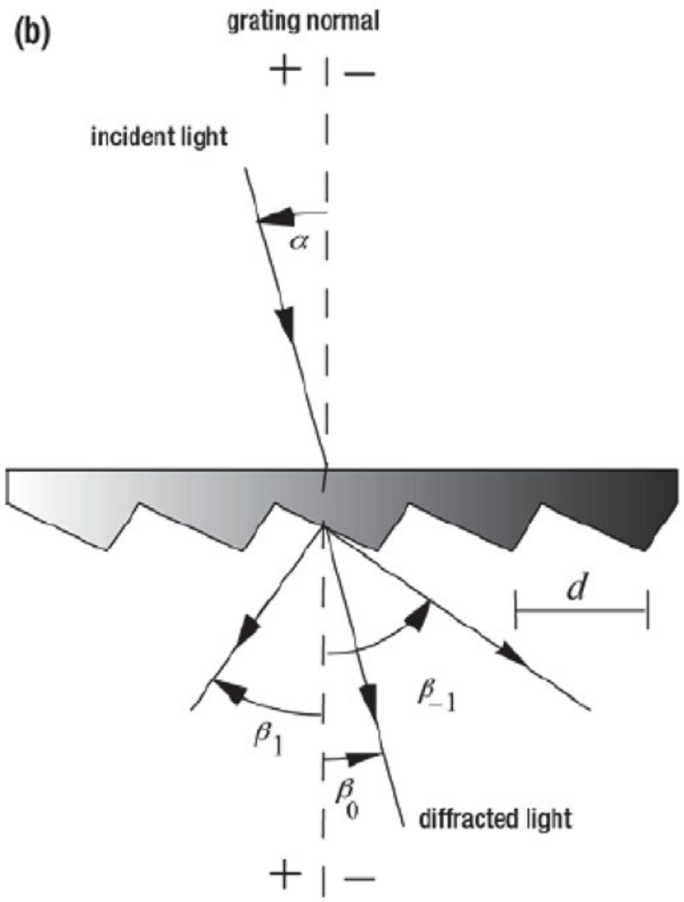
Signs depend on geometry.



Reflection grating geometry

The grating equation:

$$m\lambda = d\,\{\sin\alpha \pm \sin\beta\}$$



Transmission grating geometry

Getting the sign of diffractive orders

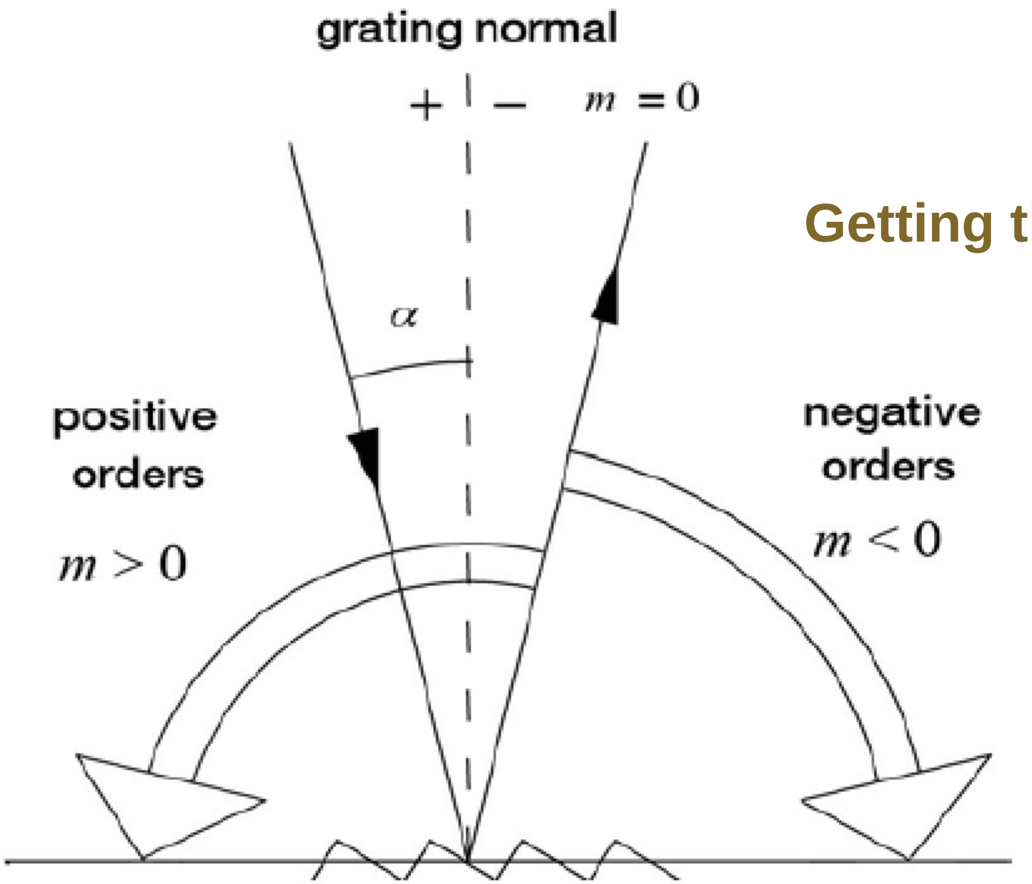


Figure 2-4. Sign convention for the spectral order m. In this example α is positive.

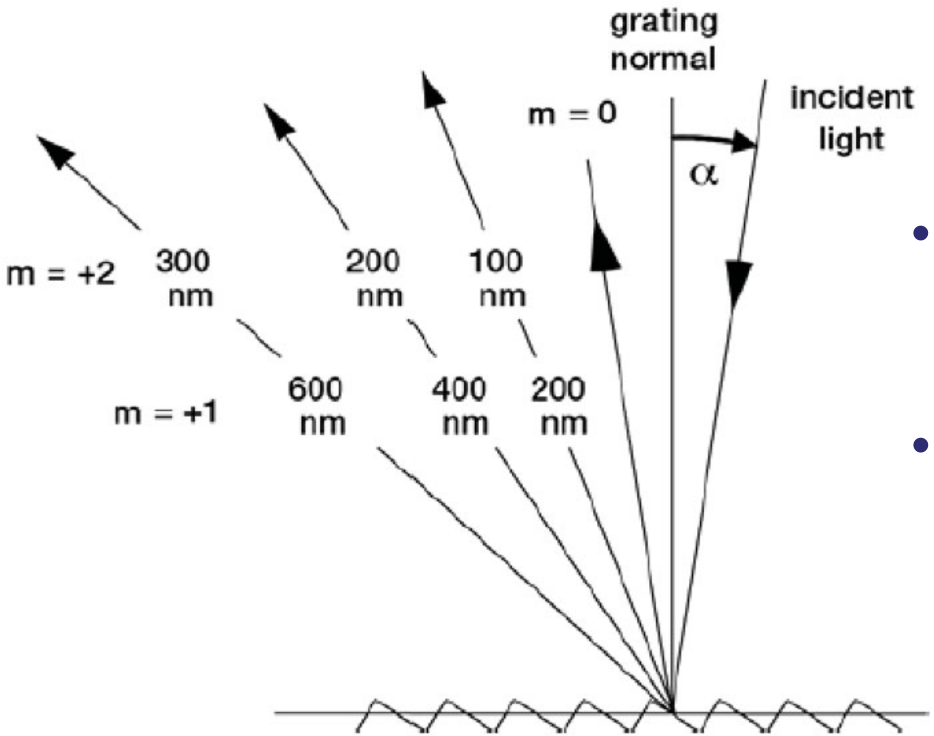
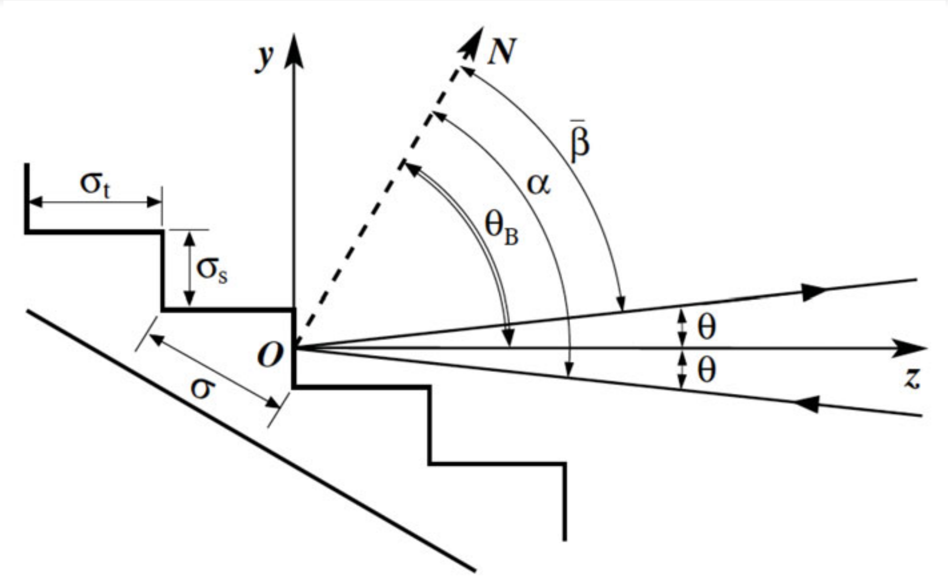


Figure 2-5. Overlapping of spectral orders. The light for wavelengths 100, 200 and 300 nm in the second order is diffracted in the same direction as the light for wavelengths 200, 400 and 600 nm in the first order. In this diagram, the light is incident from the right, so $\alpha < 0$.

- Light is diffracted into numerous orders, so it is sent into many directions.
- For high efficiency, it is desireable to send most of the light into a single order.

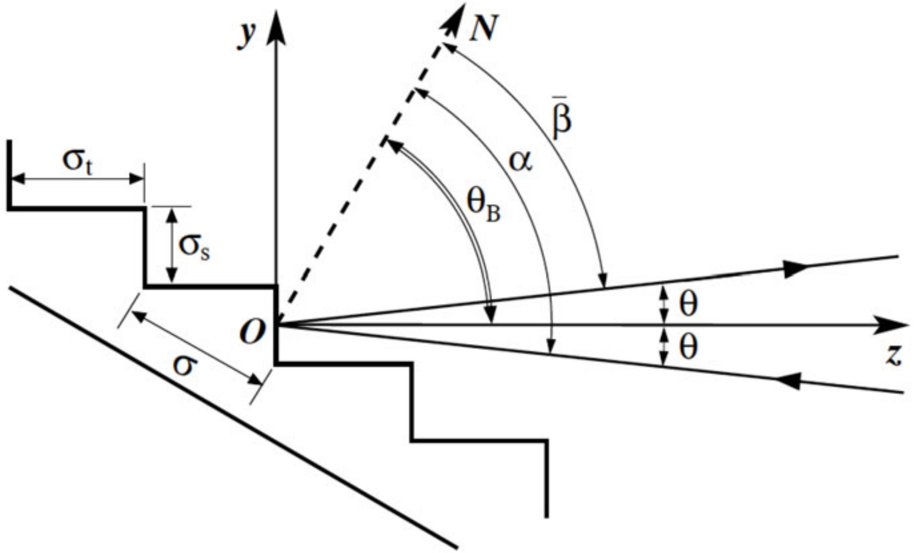


Diffraction Grating 101

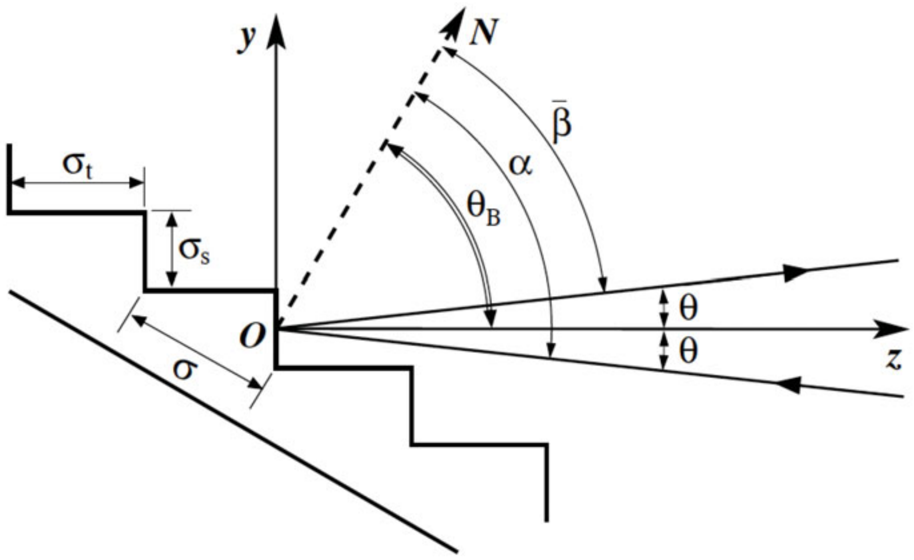
Geometry in plane of diffraction

- α is angle of incidence
- β is diffraction angle
- θ_B is blaze angle
- N is grating normal
- z is facet normal
- σ is grating pitch

Designing a Spectrograph for Natural Seeing - ”Blazing” the grating

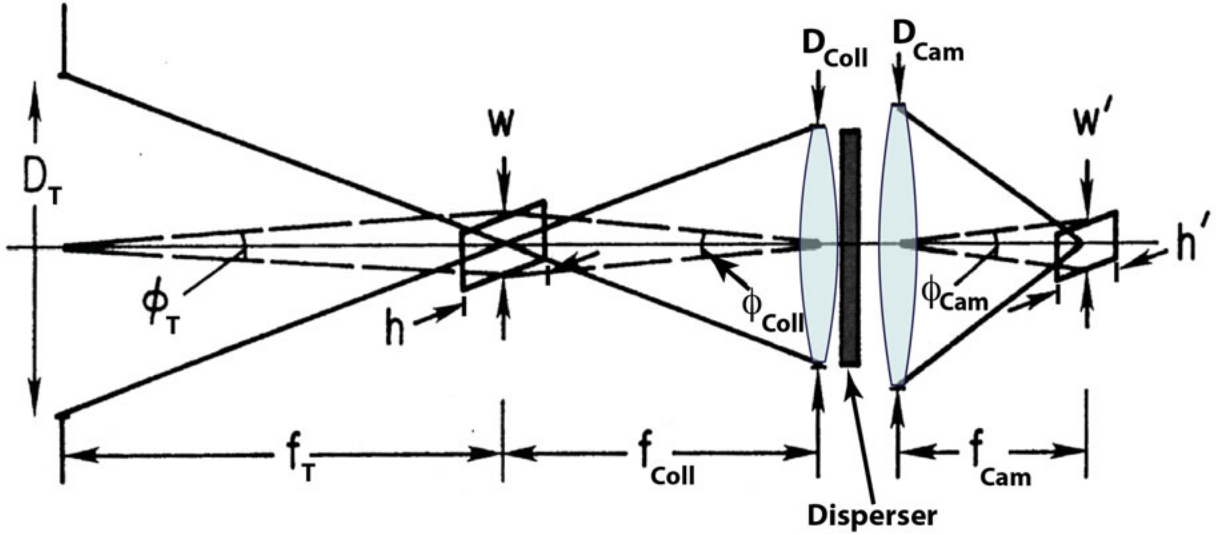


- Facet of grating are cut into numerous microscopic mirrors.
- Law of reflection: $\theta_{Incidence} = \theta_{Reflected}$
- If diffraction is arranged so α & β satsify law of reflection for a given order (m), most of the light goes into that diffractive order.
- The grating is “blazed” at θ_B for that order and wavelength.

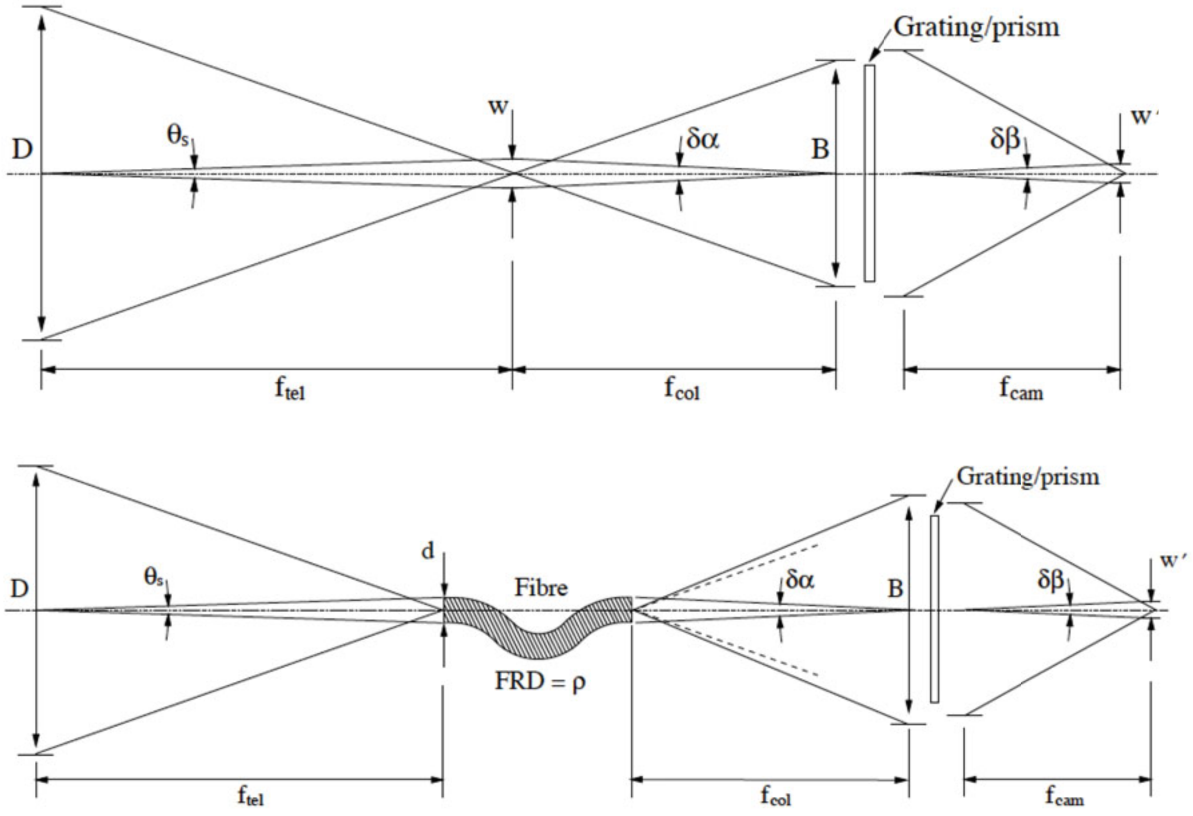


- "Echelle" = "ladder" or "stairs"
- Very high order (large m's) produce very high dispersion.
- High dispersion spread the light out radically.
- High dispersion translates into high resolution.
- Echelles with R~250,00 are possible.

The layout of a simple slit – fed spectrograph



Variable	Value
D_T, D_{Coll}, D_{Cam}	Diameter of the telescope Collimator and Camera
f_T, f_{Coll}, f_{Cam}	Focal length of the telescope Collimator and Camera
ϕ_T, ϕ_{Coll}, ϕ_{Cam}	Opening angle of the slit on the sky, at the Collimator and Camera
w, h	Linear width and height of the slit
w', h'	Linear width and height of the slit image



- Spectrographs may fed with slits (rectangular shape) or fiber-feed (round or polygonal).
- Slitless is possible too.

Spectrographs may have slits (rectangular shape) or fiber-feed (round or polygonal)

An incomplete trade study between fibers and slits

Fibers

- Geometry is fixed
- Format is fixed or limited
- Sky subtraction less perfect
- Blue transmission limited
- IR is difficult
- Very high mechanical and thermal stability achievable.
- Multiobject capability “built-in”
- Resolution ”boost”

Slits

- Slit width can be adjustable
- Slit length is adjustable
- Sky subtraction better with a long slit
- Blue transmission can extend to atmospheric limit (~3000-3200Å)
- IR is enabled
- Flexure and thermal control is a problem for Cass or Nasmyth mounting.
- Multiobject capability possible, but harder
- No resolution “boost”

A quick calculation of resolution (see notes for details):

$$R = \lambda / \delta\lambda$$
$$\lambda = d/m\,\{\sin(\alpha) \pm \sin(\beta)\}$$
$$\delta\lambda = d/m\,\{\cos(\alpha)\delta\alpha \pm \cos(\beta)\delta\beta\}$$

$$R = \{\sin(\alpha) \pm \sin(\beta)\} / \cos(\alpha)\delta\alpha \pm \cos(\beta)\delta\beta$$

For the case of an echelle spectrograph operated at Littrow (α=β):

$$ittrow = Tan\{\theta_B\} \cdot 1/\phi_T \cdot D_{Coll} / D_T$$

D_{Coll} is the diameter of the collimator

D_T is the diameter of the telescope primary

ϕ_T is the angular width of the slit in arcsec

(see notes for details)

The most important result of this lecture

$$R_{Littrow} = \tan\{\theta_B\} \cdot \frac{1}{\phi_T} \cdot \frac{D_{Coll}}{D_T}$$

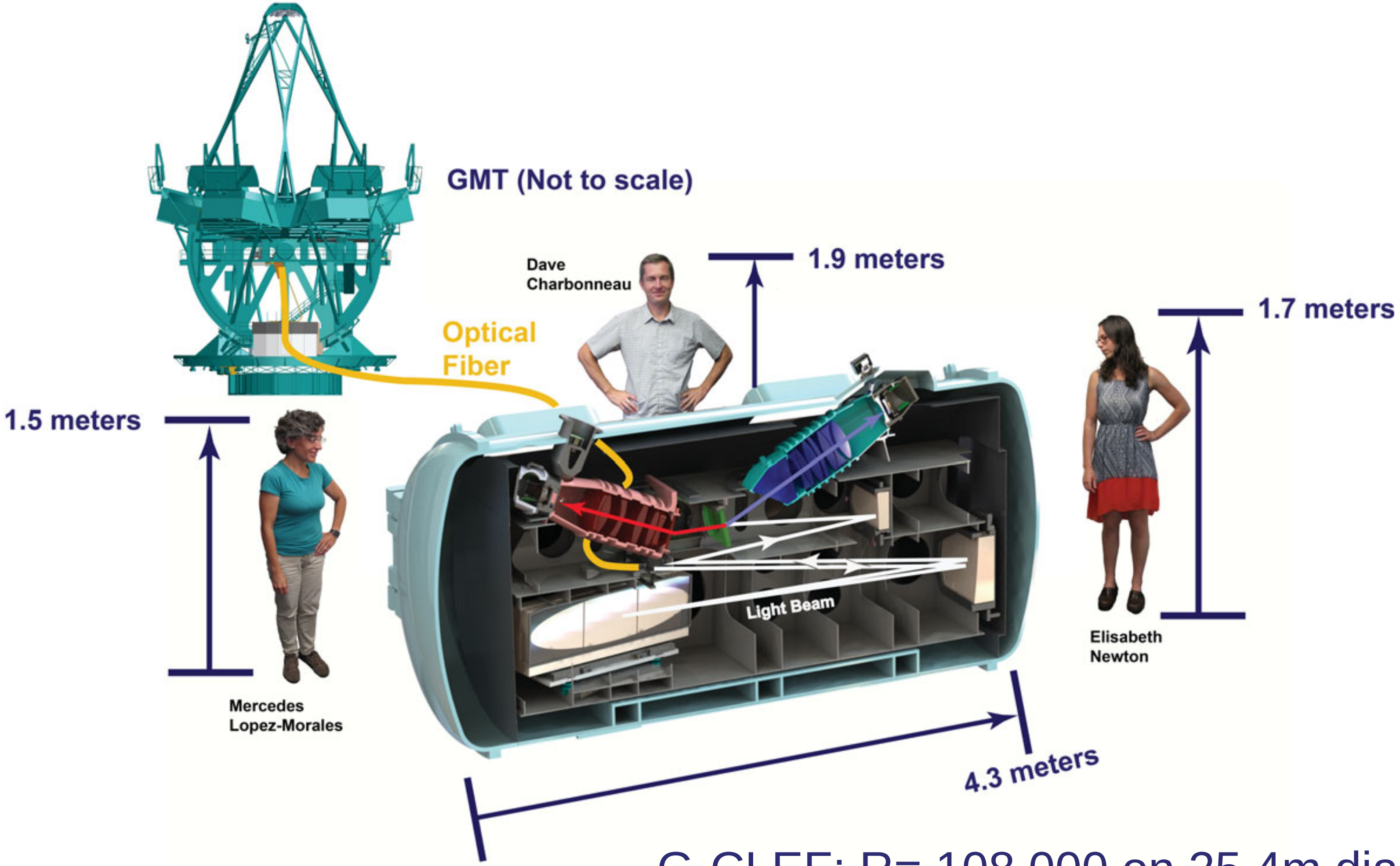
D_{Coll} is the diameter of the collimator

D_T is the diameter of the telescope primary

ϕ_T is the angular width of the slit in arcsec

- Littrow always yield the highest efficiency, and usually the highest resolution/
- The factor $\tan\{\theta_B\}$ techologically limited: $\tan\{\theta_B\} \leq 4$.
- The angular slit size is set by nature:
  - $\phi_T \sim 1\ arcsec$ Natural Seeing ; $\phi_T \sim 10\ milliarcsec$ AO Correction
- You choose D_T when you build your telescope.
- To increase resolution, all you can do is make D_{Coll} bigger.
- When you make D_{Coll} bigger, you make the spectrograph bigger.
- When you make the instrument bigger, you make it more expensive.
- For D_{Coll} larger that 300 mm, extraordinary costs, designs or means are required.
- Very few optical glasses (used to make lenses) are produced larger than 300 mm

Big Telescopes mean
Big (Expensive) Instruments



G-CLEF: R= 108,000 on 25.4m dia. aperture telescope

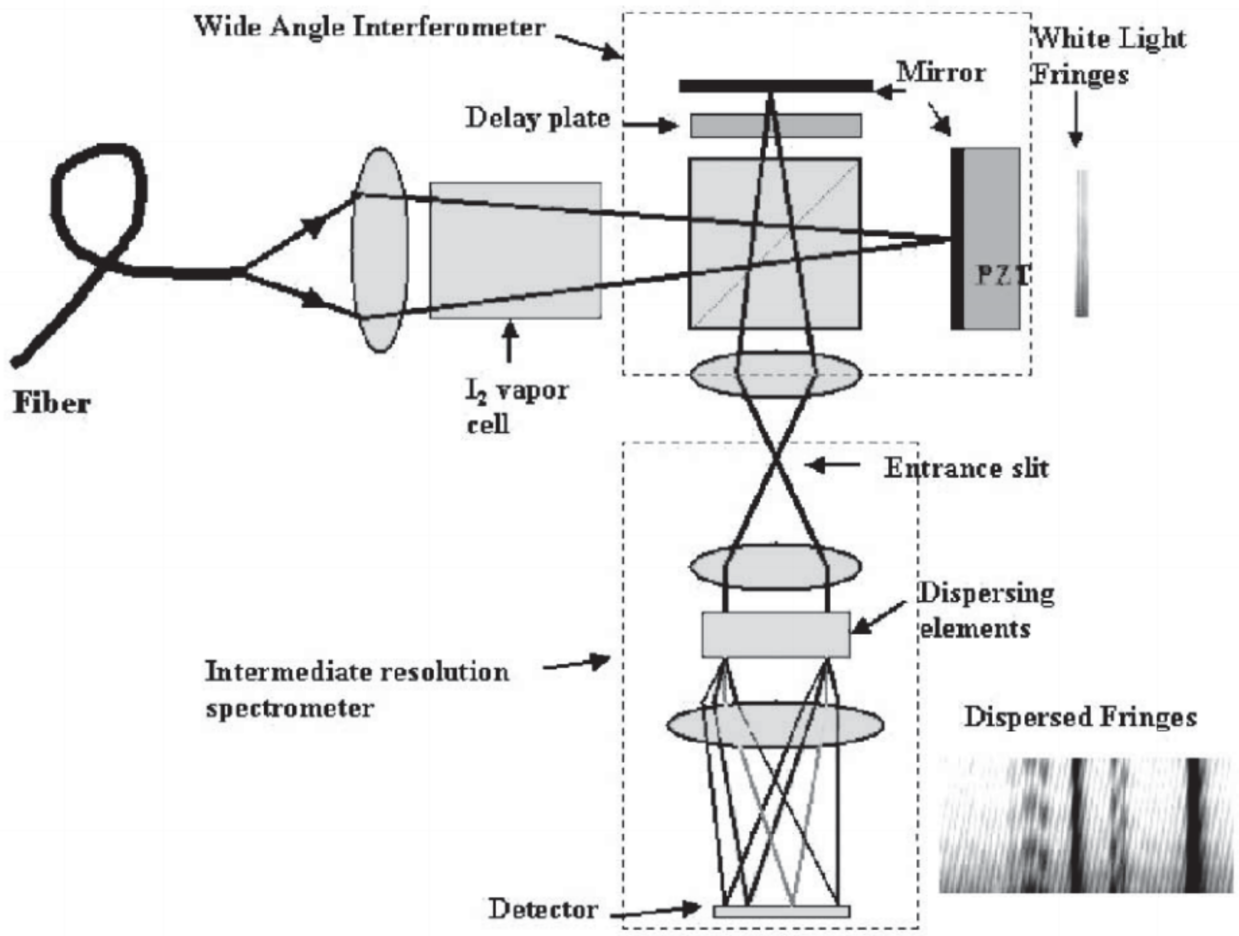
Many astrophysical program require R~100,000

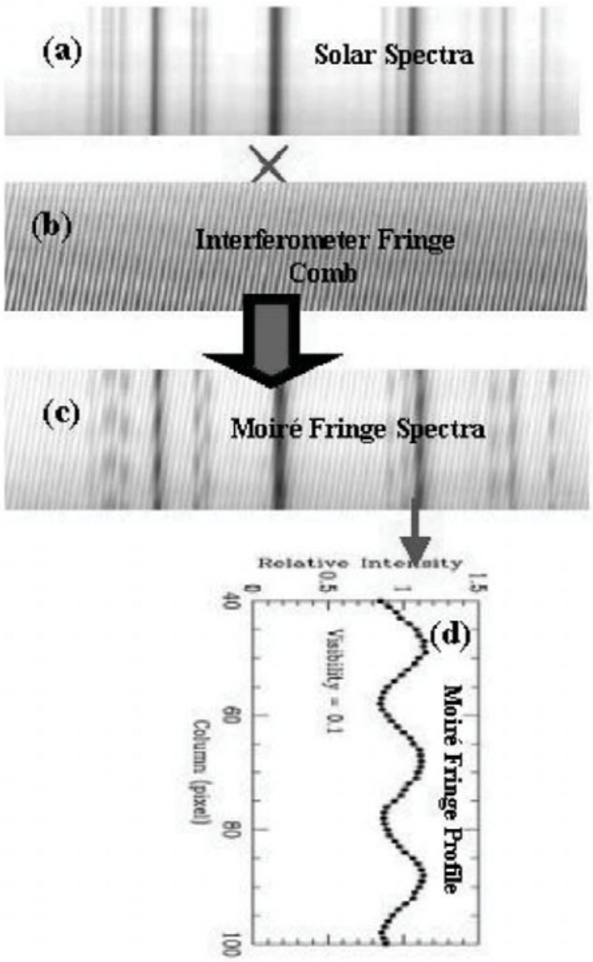
- Precision radial velocity
- L_α forest, &c.
- Exoplanet atmospheres

Exoplanet atmospheres really optimal at R~300,000 - 500,000.

What to do?

Getting to R=300,00
Externally Dispersed Interferometers for O_2 Searches


Wide Angle Interferometer
White Light
Fringes
Mirror
Delay plate
PZT
Fiber
I_2 vapor
cell
Entrance slit
Dispersing
elements
Intermediate resolution
spectrometer
Dispersed Fringes
Detector



EDI spectra are the convolution of the low resolution spectrum and interferometer fringe pattern.

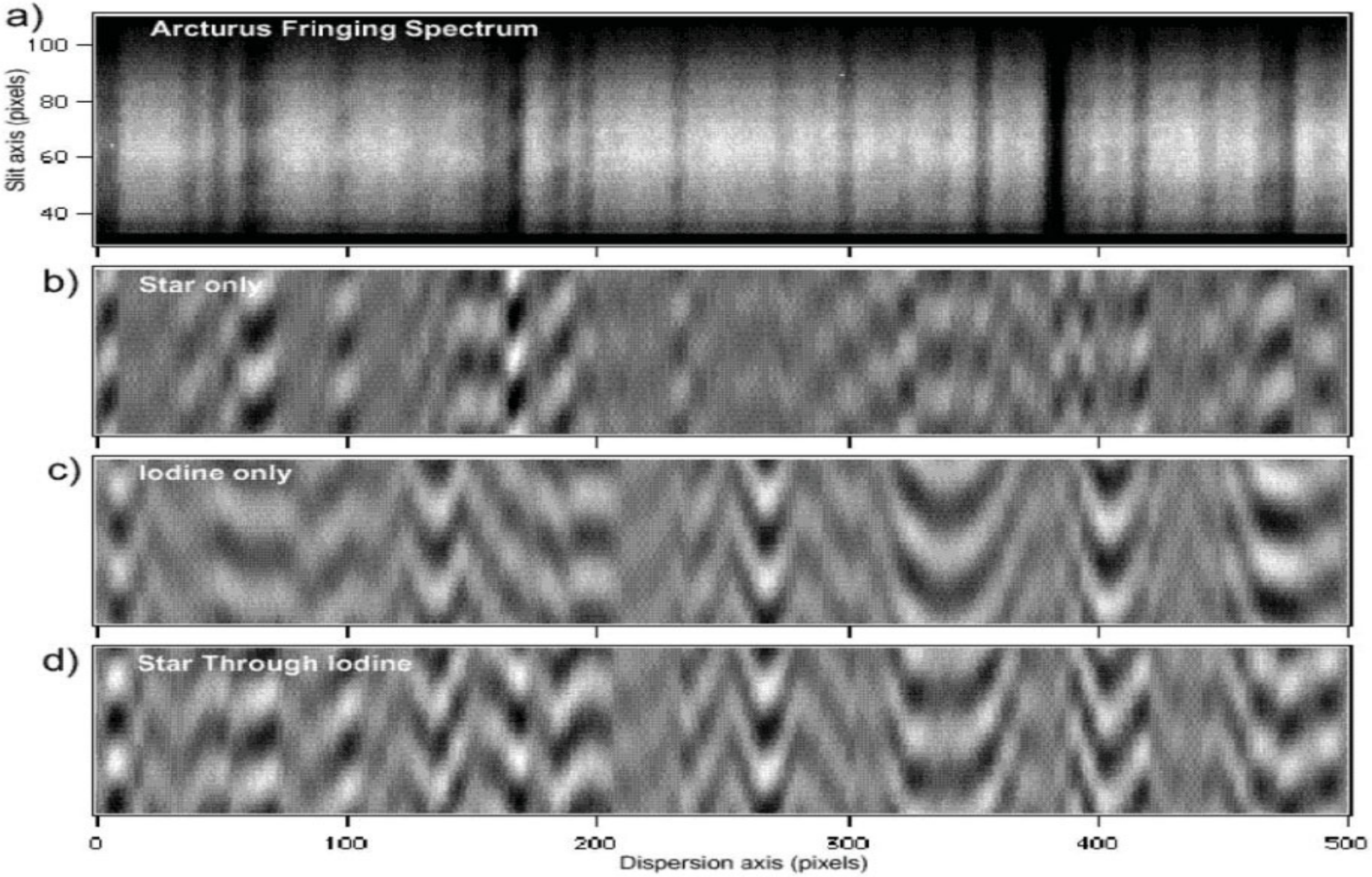
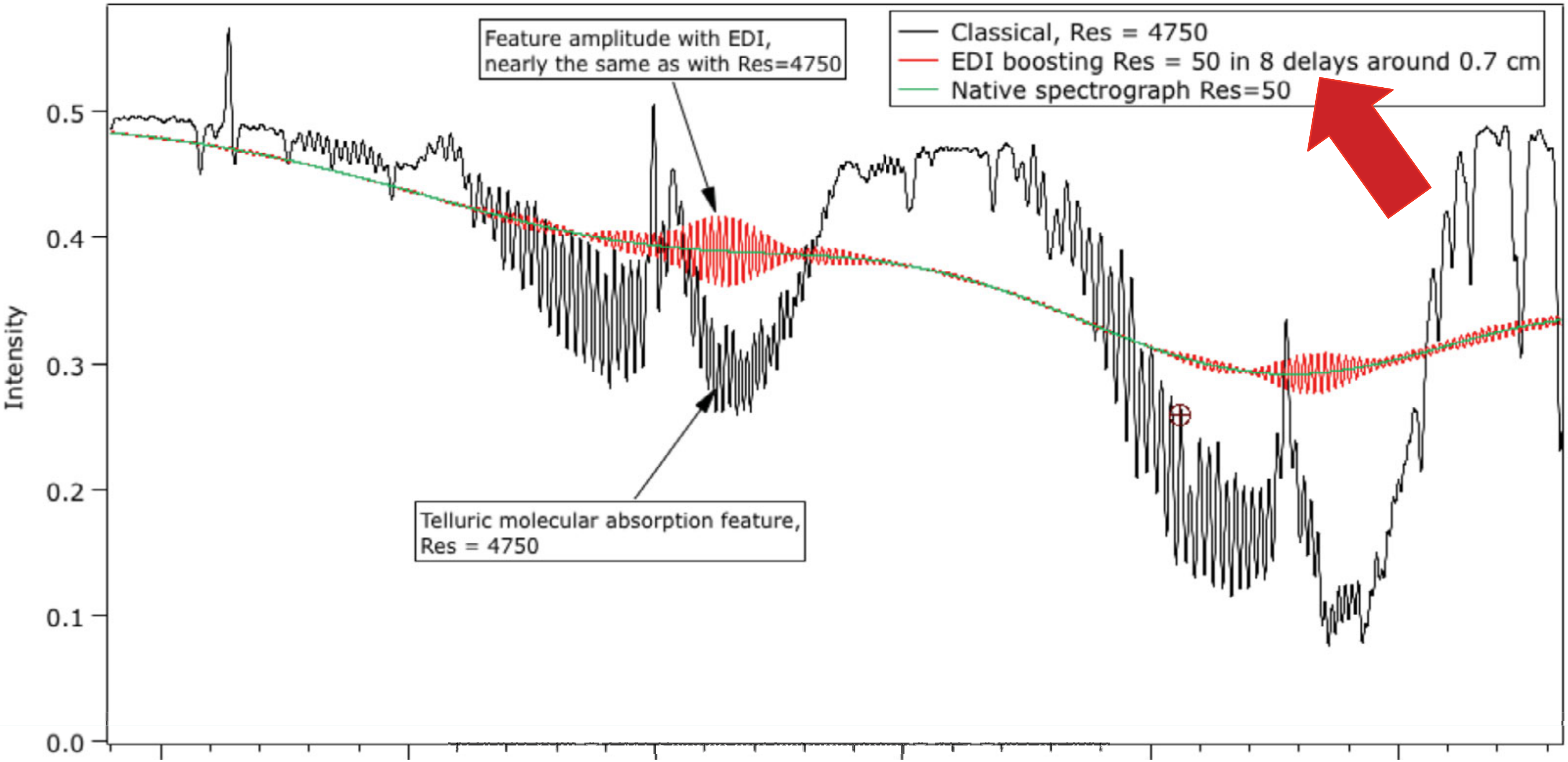


FIG. 6.—(*a*) Stellar moiré fringes of nearby star, Arcturus, taken by the fiber-fed EDI in 1999 December. (*b*), (*c*), and (*d*) are the fringing nonfringing components have been removed during the data reduction process, for (*b*) the star alone, (*c*) iodine cell alone with a tungsten lamp, through the iodine cell. The underlying interferometer sinusoidal comb has been optically filtered away by the blurring action of the spectrog configured to have lower resolution than when used in lab tests.

“Spectrum” Recovered form EDI Spectropgraph is Complicate



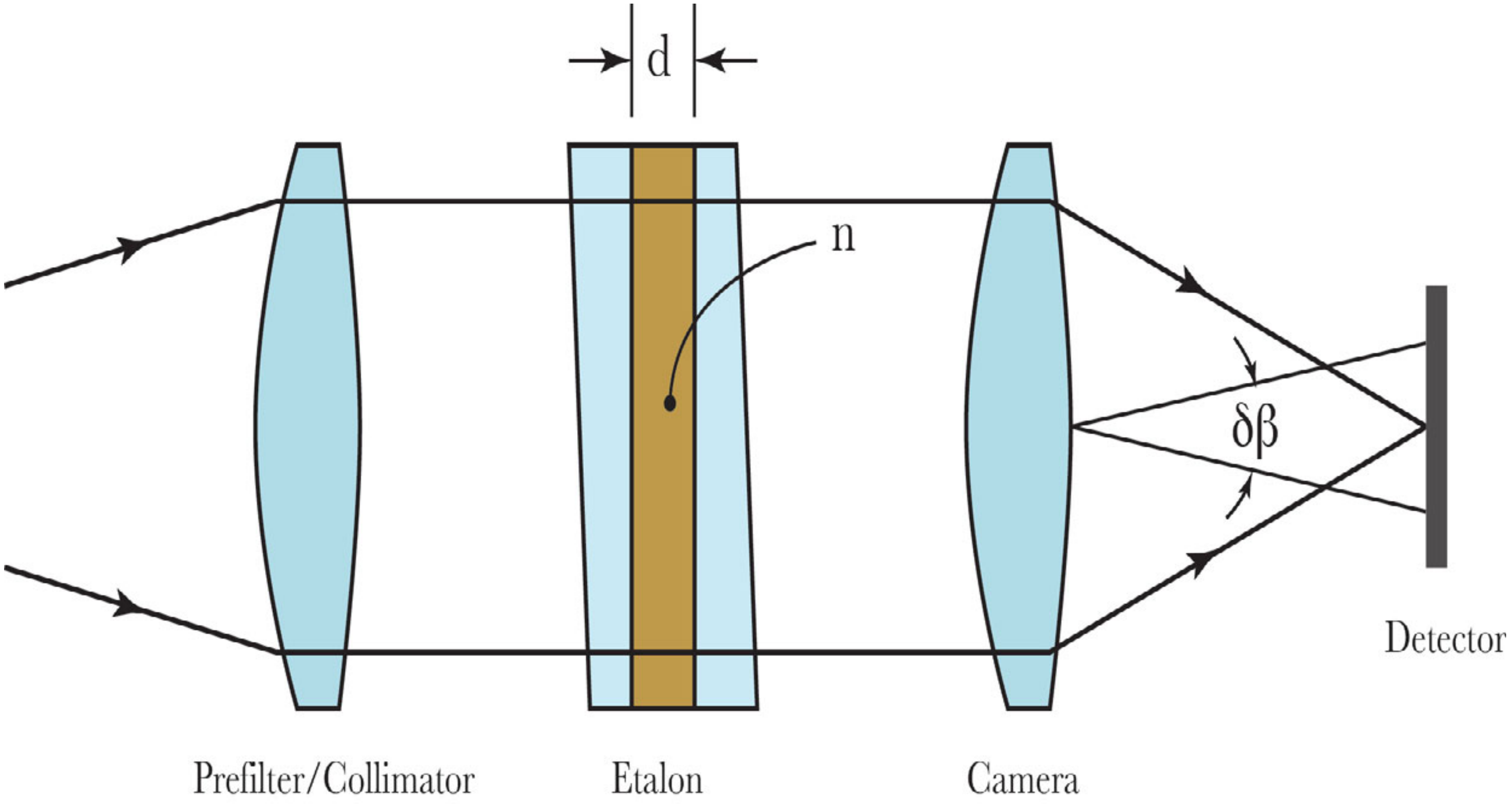
- 8 Delays means 8 observations.
- The cost of the instrument is low.
- The cost in observing time is high.
- Observing time on the GMT will be very, very expensive.

However, the path to R=300,000 not clear, the science rewards are huge, so every avenue should be pursued.

Getting to R = 300,000
A Very High Resolution Fabry-Perot for O_2 Detection

Getting to R = 300,000
A Very High Resolution Fabry-Perot for O_2 Detection

A Fabry perot Interferometer for Oxygen Searches (FIOS)


d
n
δβ
Detector
Prefilter/Collimator
Etalon
Camera

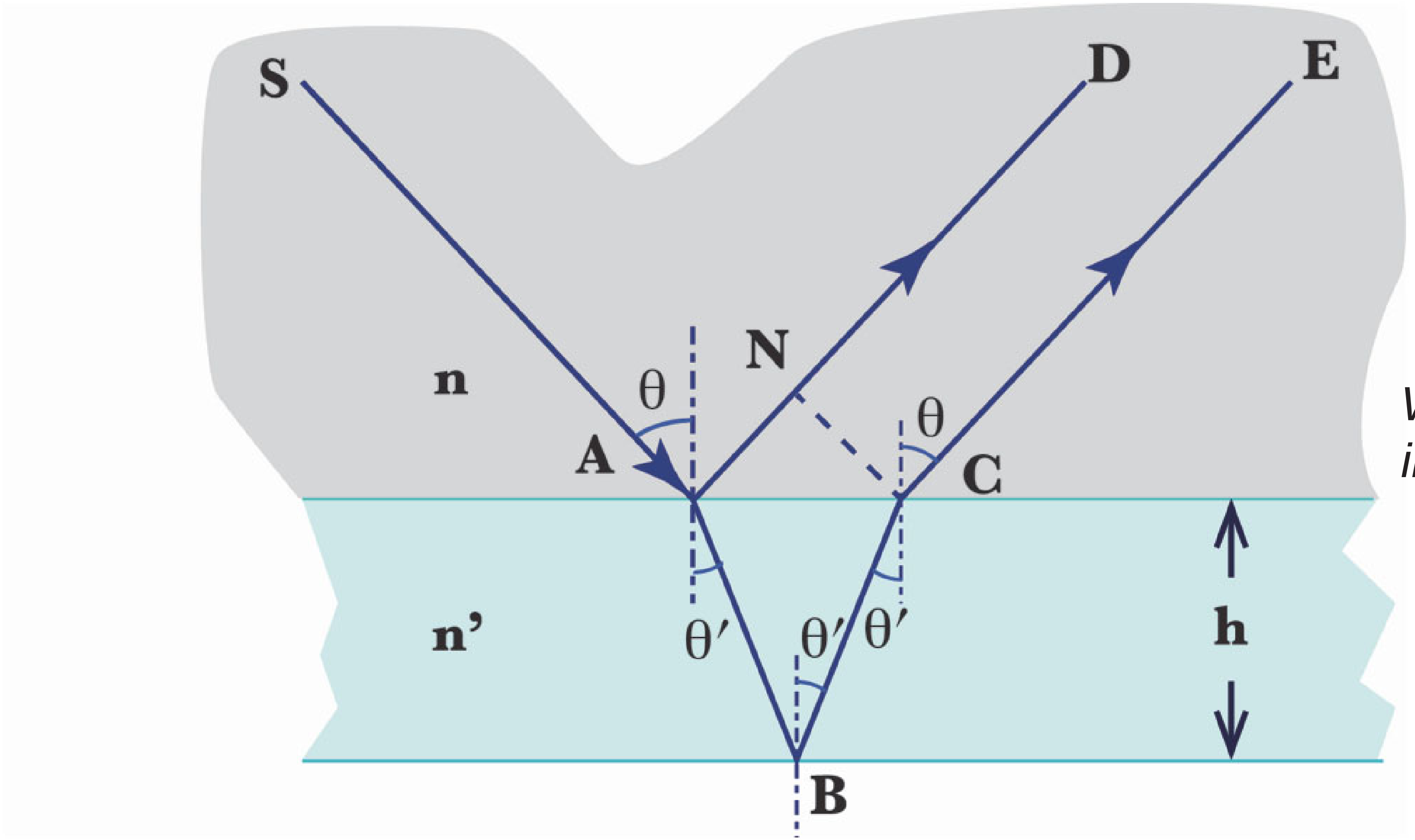
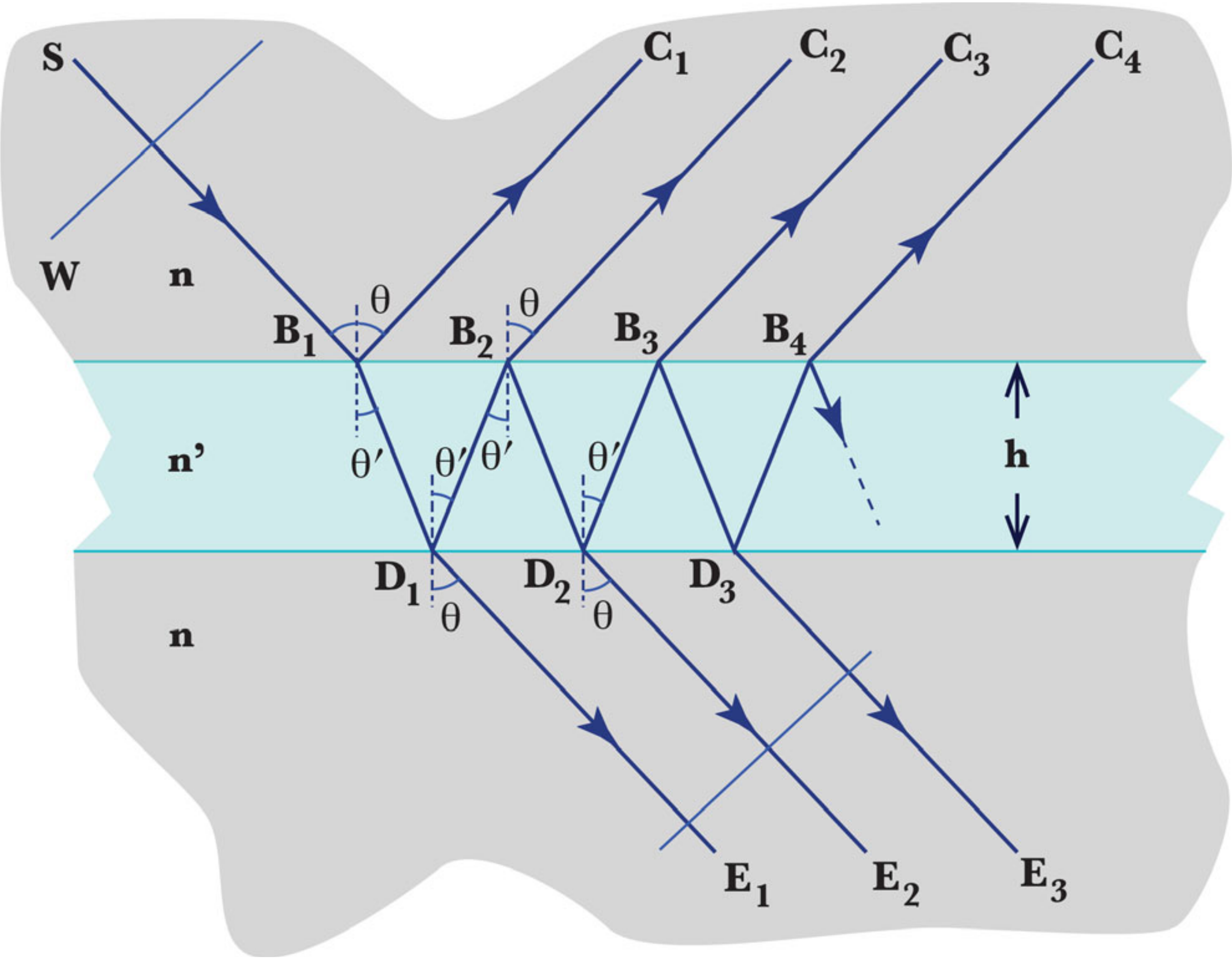


Figure 5: The ΔOPD between points A and C is the length AN.

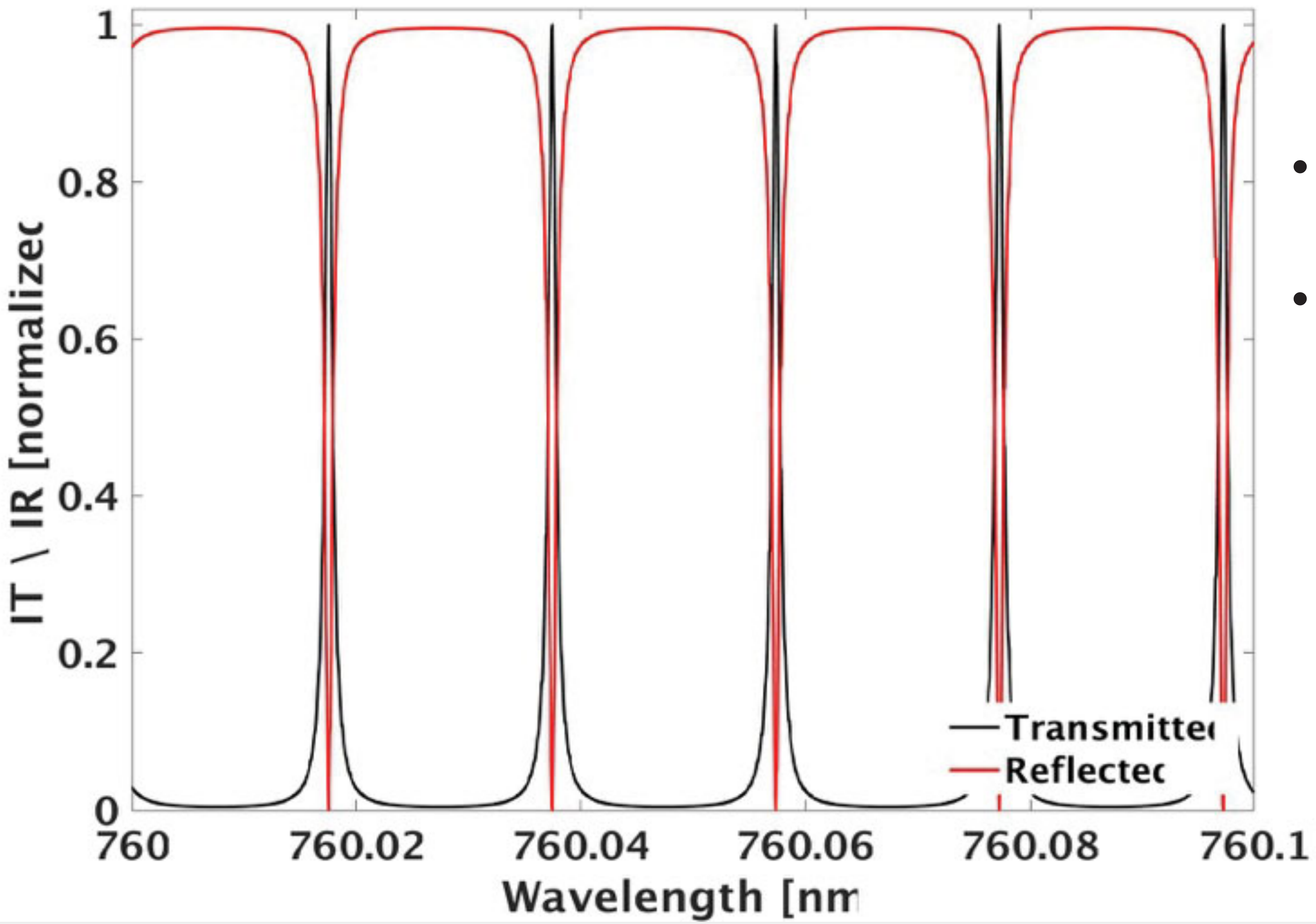
When $\Delta OPD = n\lambda$ interference in beams D & E is constructive

FIOS – A Fabry-Perot Produces a Transmitted Spectrum



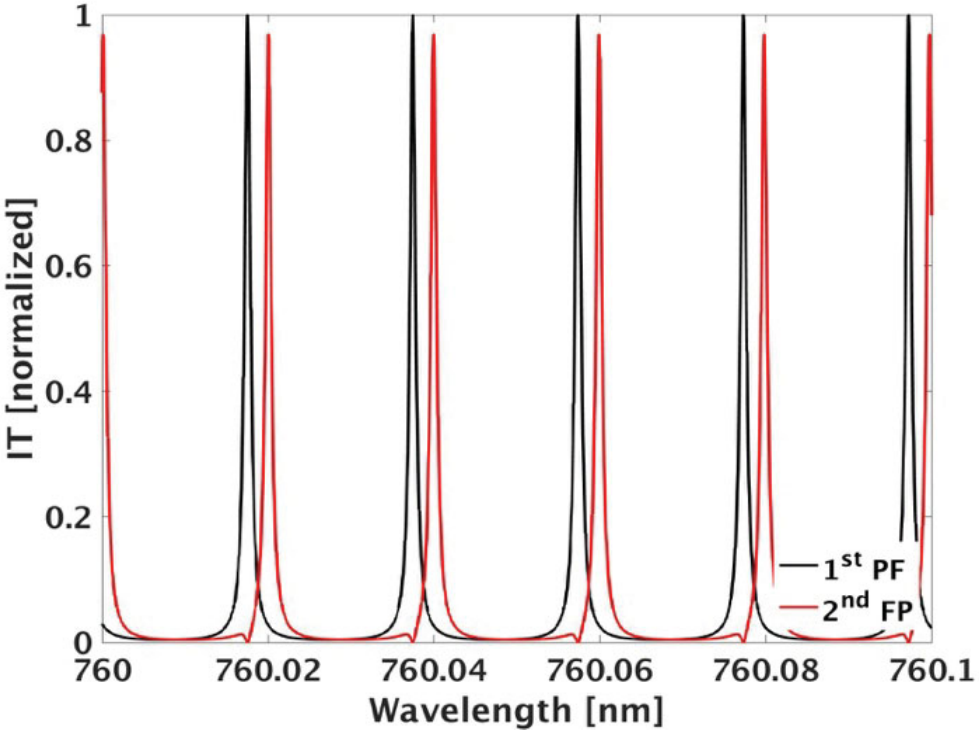
The interference is enhanced by multiple beams

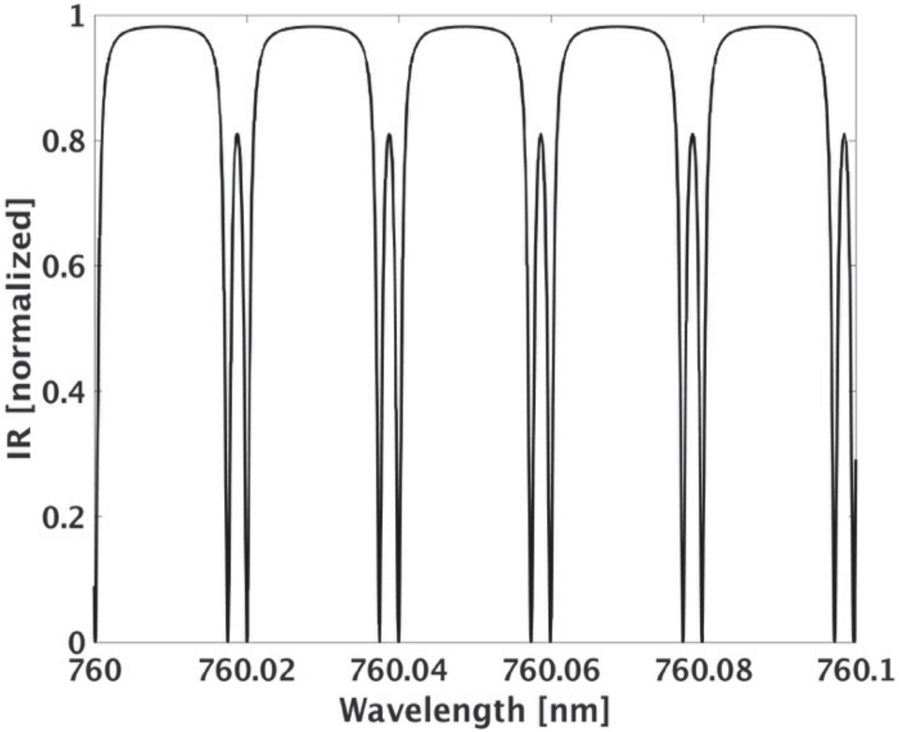
FIOS – Reflected and Transmitted Spectrum A Fabry-Perot Spectrum



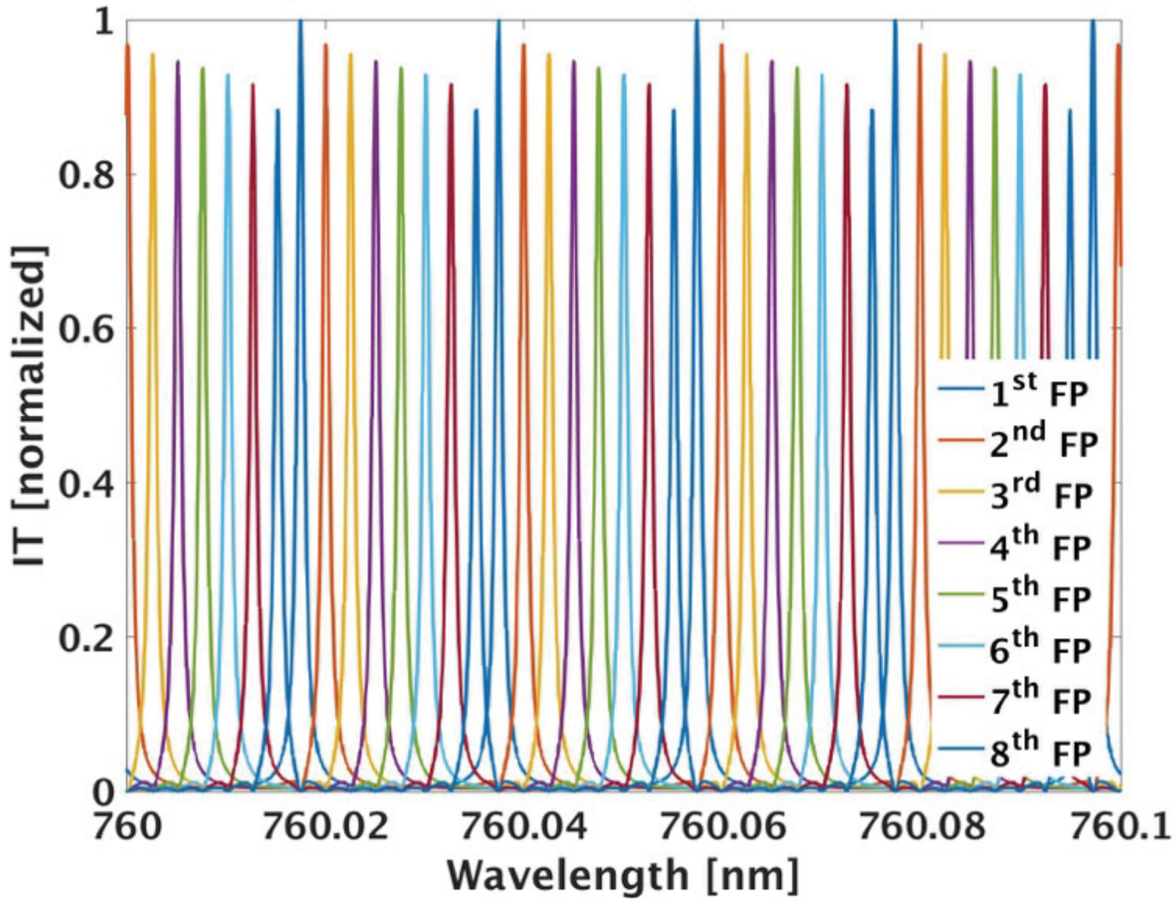
- What isn't reflected is transmitted.
- The ratio of the width of the transmitted or reflected beam is the "finesse" of a Fabry–Perot.

FIOS – Reflected and Transmitted Spectrum of Fabry-Perots in Series

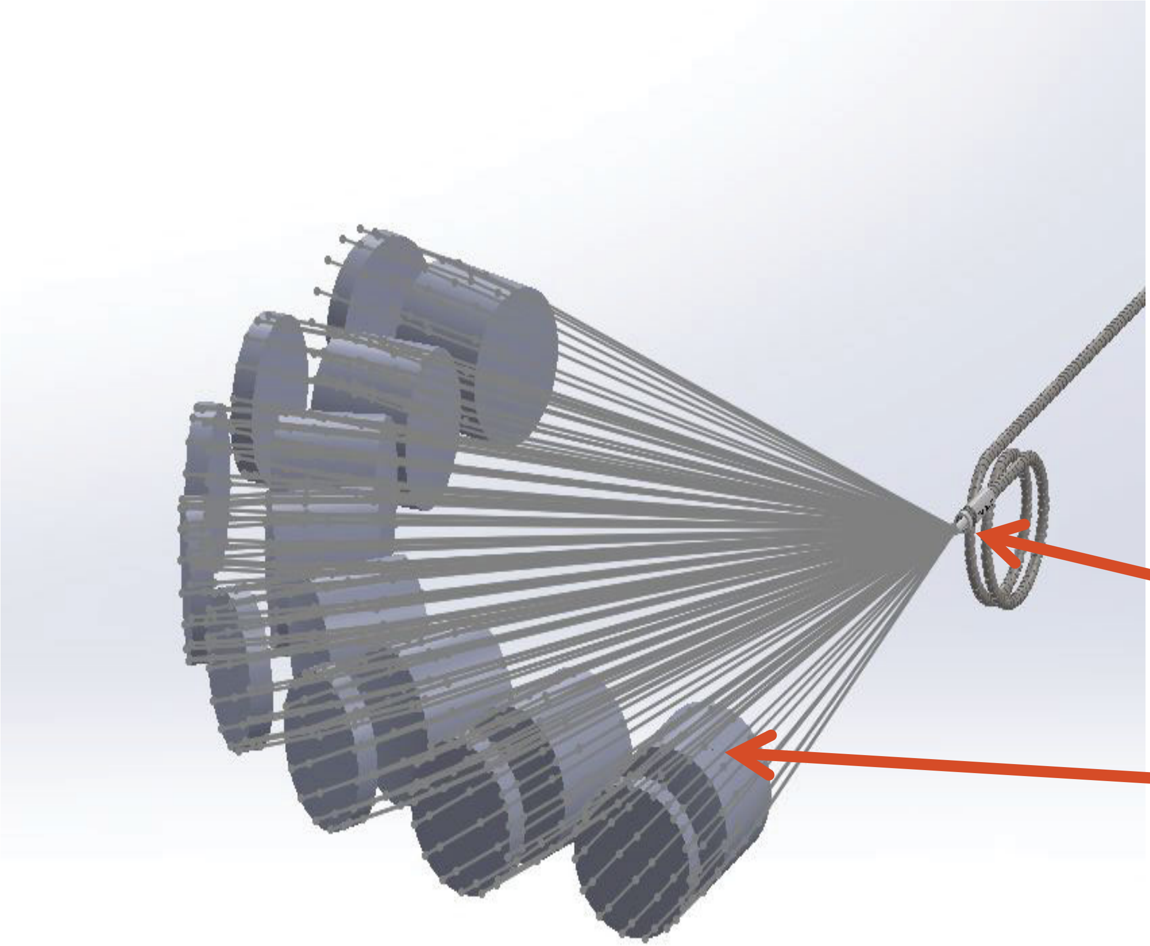




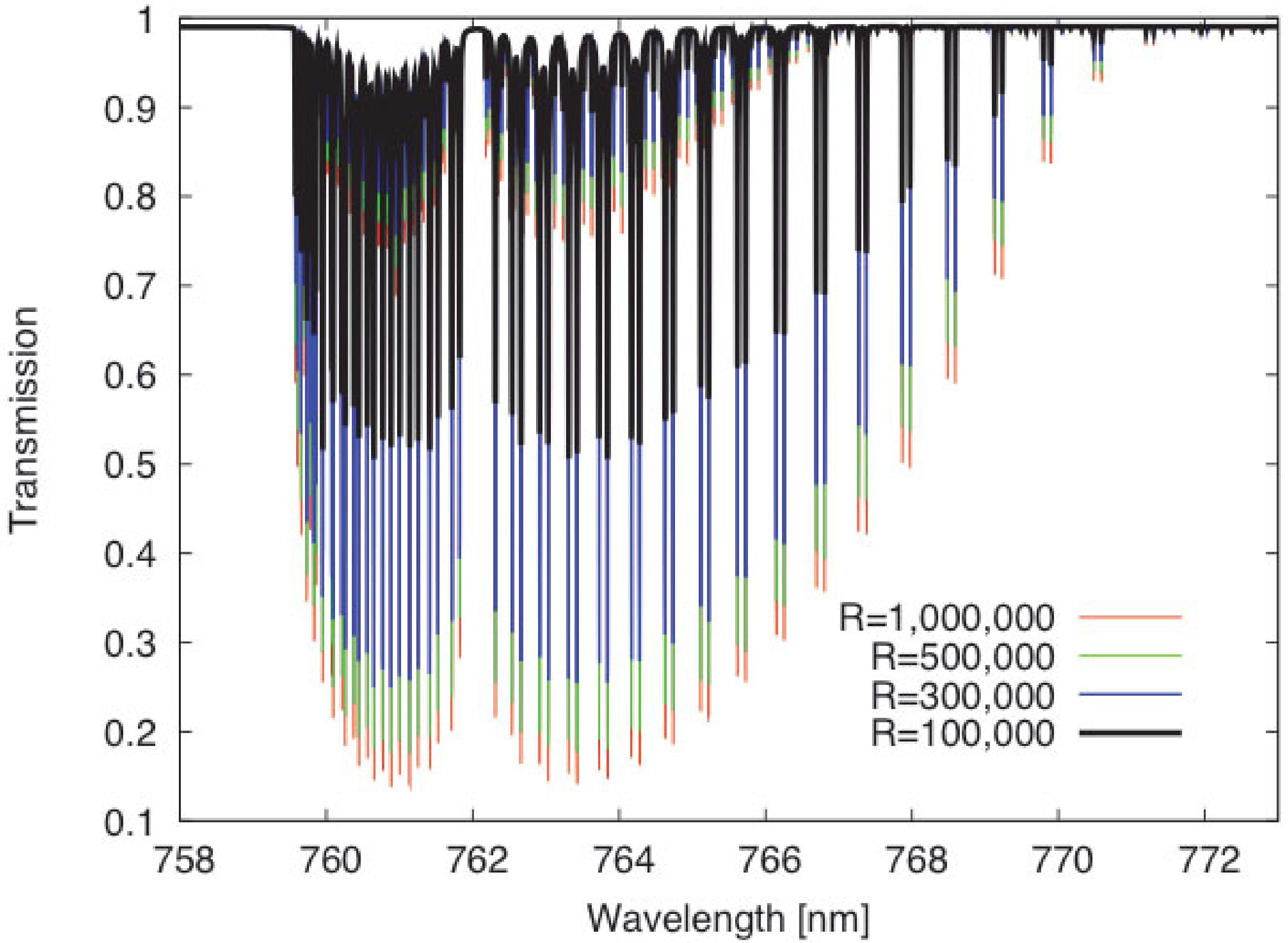
Multiple Fabry-Perots (etalons) broaden the spectral coverage.



- Multiple etalons provide full spectral coverage
- The number of beams required depends on the finesse of the etalons



The beam is cycle through numerous etalons with a polygonal mirror.



Finesse is adjust to provide
R = 300,000 - 500,000

FIOS – Why Does FIOS Work?

How did we beat:

$$R_{Littrow} = Tan\{\theta_B\} \cdot 1/\phi_T \cdot D_{Coll}/D_T$$

i.e.: How did we violate the 2^{nd} law of thermodynamics?

FIOS operates over a very restricted range of wavelengths (~100Å).

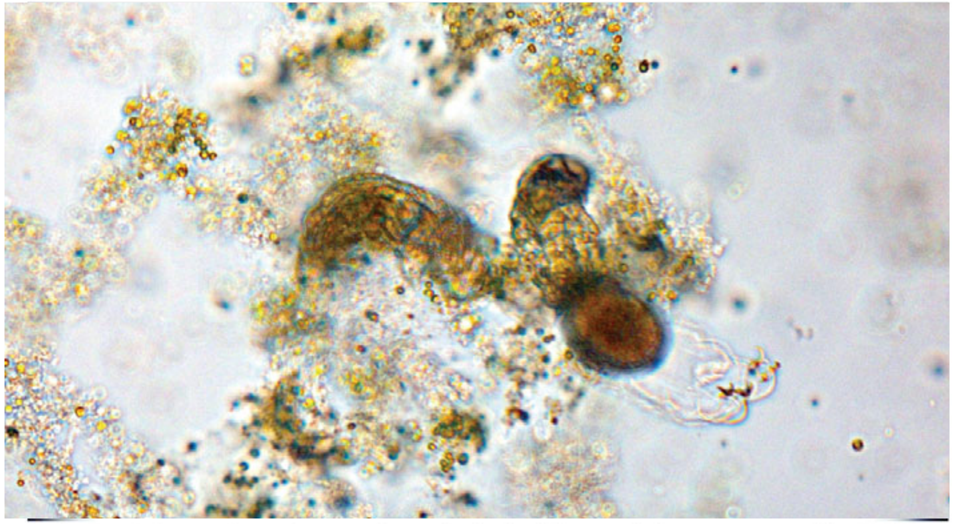
A FIOS that operated over 7000Å would be 700 ×larger, i.e., very, very big.

The Washington Post
Democracy Dies in Darkness

Speaking of Science

These animals can survive until the end of the Earth, astrophysicists say

By **Ben Guarino** July 14, 2017 Email the author



Tardigrades, also known as the water bear, are microscopic animals, which can survive in many extreme conditions, including space. (Taylor Turner/The Washington Post)

Tardigrades have a reputation as the toughest animals on the planet. Some of these microscopic invertebrates shrug off temperatures of minus 272 Celsius, one degree warmer than absolute zero. Other species can endure powerful radiation and the vacuum of space. In 2007, the European Space Agency sent 3,000 animals into low Earth orbit, where the tardigrades survived for 12 days on the *outside* of the capsule.

Sloan, with his Oxford colleague Rafael Alves Batista and Harvard University astrophysicist Abraham Loeb, decided to try to rid the planet of tardigrades. In theory, anyway, in a report published Friday in the journal Scientific Reports. Through the powers of mathematical modeling they tossed three of the most devastating cosmic events at Earth: killer asteroids, supernovae and gamma-ray bursts.

“These are the biggest ways you can transfer energy to the planet,” Sloan said. The tardigrades kept on theoretically trucking, outlasting 10 billion years' worth of cataclysms. Until the point that the sun failed or engulfed the planet.

In picking their apocalyptic poison, the scientists first tried to sterilize the planet with radiation. In the lab, some tardigrade species can survive radiation doses of 5,000 to 6,000 grays. (“You would be very, very lucky to walk away” from a dose of 5 grays, Sloan said.) But long before the scientists blasted Earth with enough radiation to kill all the tardigrades, they calculated that the radiation's energy would boil the oceans away. The sticking point for tardigrades, then, was the evaporation of the planet's water.

For an asteroid to deposit that much energy into the ocean, it would need a mass of at least 1.7 quintillion kilograms. Of all the asteroids in the solar system, only 19 fit the bill. (By way of comparison, the asteroid that finished the dinosaurs was six miles across; an asteroid called Vesta that is one of the potential ocean killers has a diameter of 326 miles.) The chances of such a massive collision are so small, the scientists said, that the sun would die first.


When we look at life on other worlds, it may be tardigrades that look back at us.

The Tardigrade is the official G-CLEF mascot