Ring Seismology Status Update

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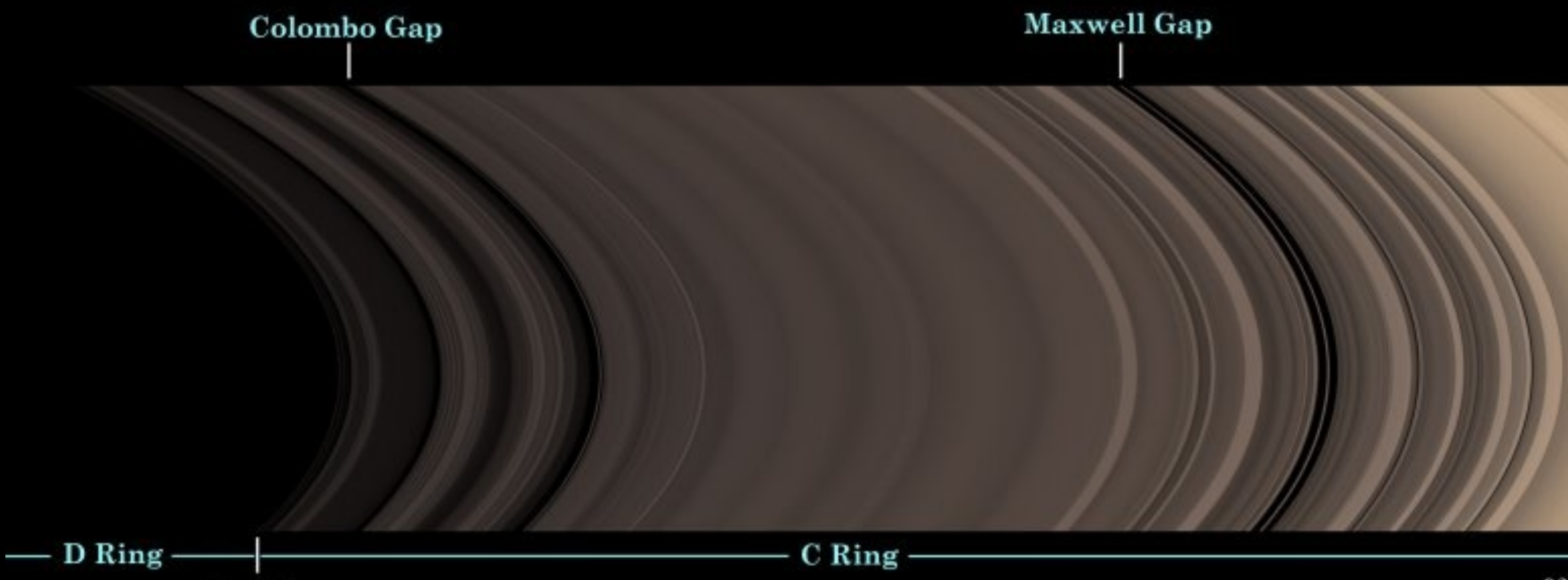
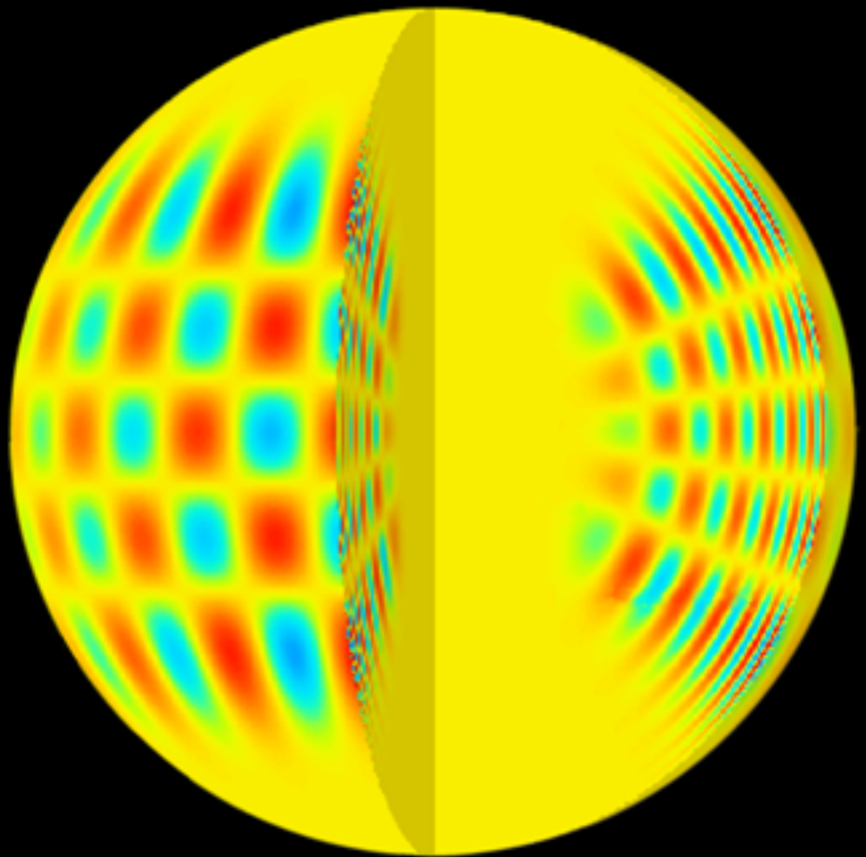
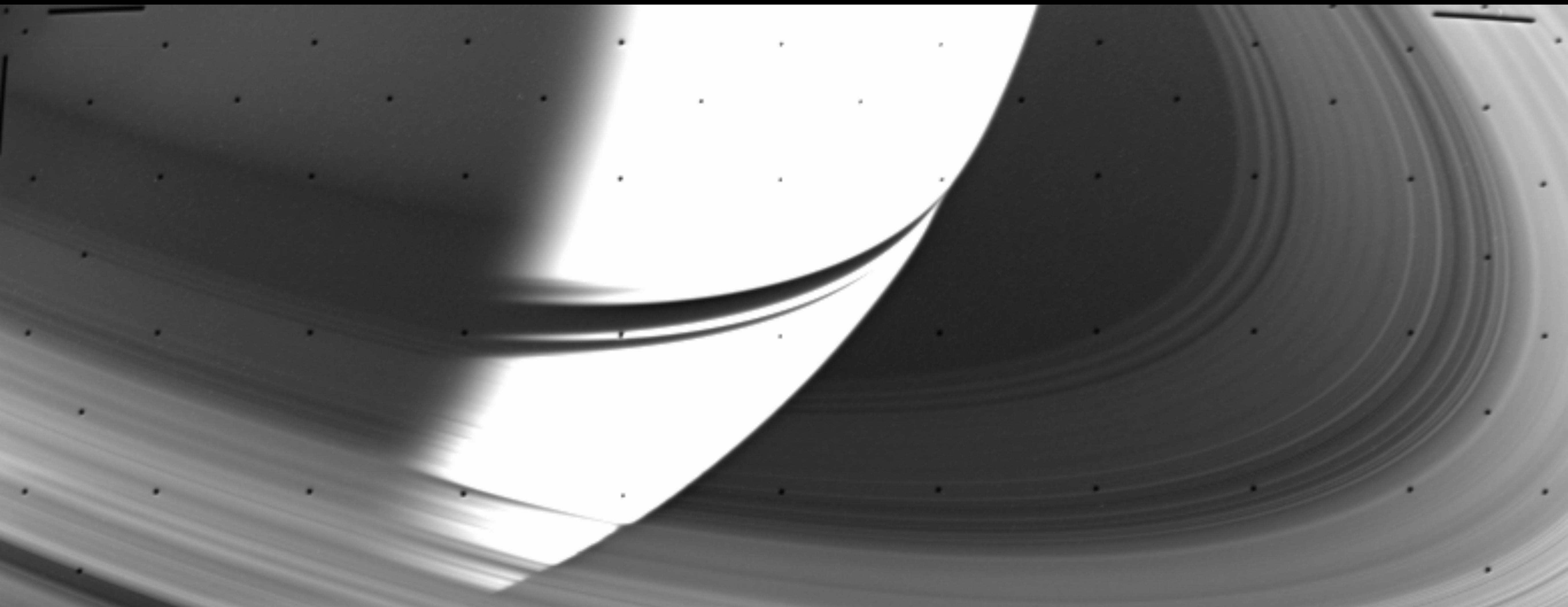
NASA Ames



Science Context

- Discovery & exploitation of solar oscillations: mid to late '70s
- Voyagers at Saturn: 1980 & '81

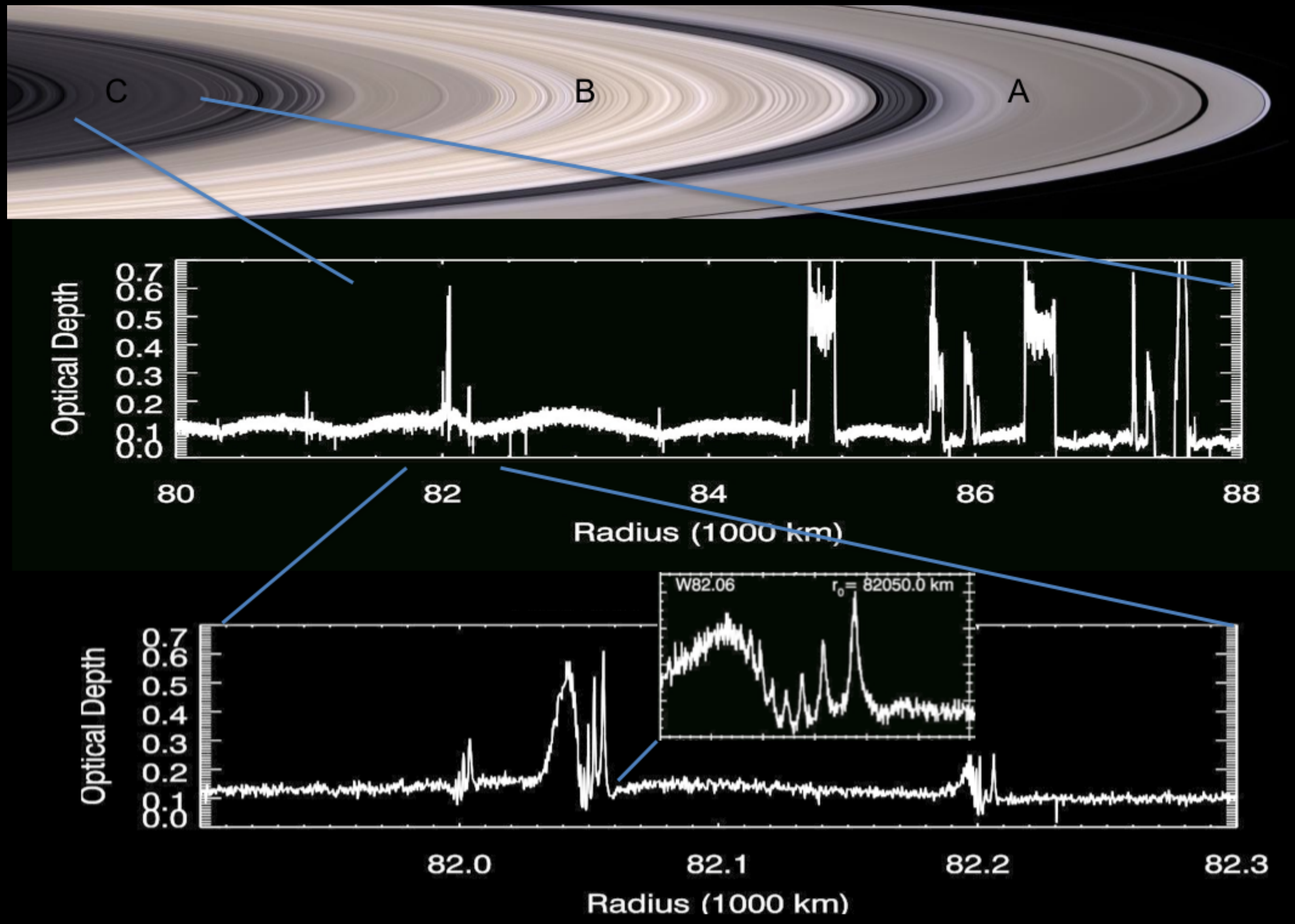




Unassociated C-Ring Feature Locations

Location (km)	$\delta\tau/\tau_n$	m	Wave type
87,400	--	--	Maxwell gap
74,945	1.2	2-3	OVR/ILR
80,990	1.0	3-11	OLR/IVR
82,065	1.1	2-4	OLR/IVR
82,211	1.2	2-5	OLR/IVR
83,638	0.9	3-7	OLR/IVR
84,650	1.2	2-5	OLR/IVR
85,465	2.0	1-2	OLR/IVR (if m=2)
85,690	2.3	1-3	OVR/ILR (if m>1)

Table I. Unexplained features in the C ring. Table by Marley and Porco (1993) using data from Rosen et al. (1991b)



Origin of Idea

- Dave Stevenson: 1982 AGU
  - Resonances between planet modes & ring orbits
  - Considered: p-modes & inertial modes
  - Focused on inertial modes

Are Saturn's Rings a Seismograph for Planetary Inertial Oscillations?

D.J. STEVENSON (Div. of Geological & Planetary Sciences, Caltech, Pasadena, CA 91125)

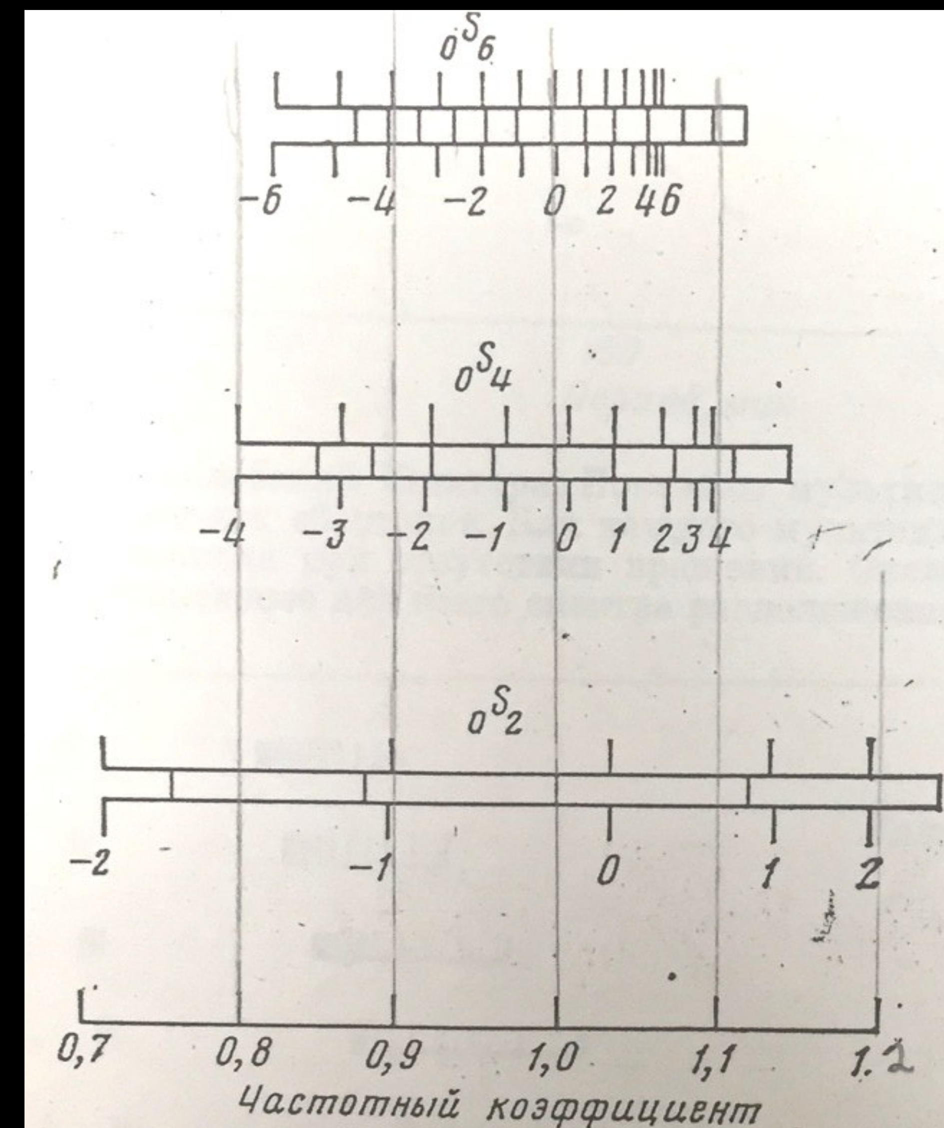
In adiabatic, fluid sphere, the normal modes include both the well-known high frequency, gravity dominated p-modes and the lower frequency Coriolis-dominated inertial oscillations. In the limit $\Omega R \ll c$ (Ω = planetary angular velocity, R = planetary radius, c = sound speed), the inertial mode frequencies are in the range $(0, 2\Omega)$. Consequently, any finite radial zone of Saturn's rings has within it a countable infinity of resonances between ring particle orbits and non-axisymmetric inertial modes of Saturn. For a given mode of velocity amplitude u and wavevector k, the associated density perturbation within the planet is $\sim \bar{\rho}(u/\Omega R)(\Omega^2/\omega_o^2 + c^2k^2)$, where $\omega_o^2 = 4\pi G\bar{\rho}$ and $\bar{\rho} \sim 1$ gm/cm^3. Consequently, the external gravity field $\propto k^{-4}$ for $kR \gg 1$ and the necessary condition for a significant effect on ring particle distribution is $u \gtrsim (0.1$ cm/s$)(kR/\pi)^4$. Mixing length theory predicts large scale convective velocities ~ 10 cm/s, but these motions do not couple effectively to the wave field. Smaller scale motions (overturn time $\sim$ wave period) achieve approximate energy equipartition ($u \sim 0.1$ cm/s) but $kR/\pi \gg 1$. However wave-wave interactions cause an inverse cascade of energy from large k to small k modes. Low-k modes are highly non-dissipative, possibly coherent for long periods, and amplitudes ~ 10 cm/s are expected from the reverse cascade. Axisymmetric zonal flows can also feed these non-axisymmetric modes by parametric instabilities. There is much structure in the rings which has not yet been explained by other processes (resonances with satellites, spiral density waves, imbedded moonlets, diffusional instabilities). A problem with the process described here is that although it may create density gradations or even gaps, it is very democratic (all of the rings should be equally affected). Possible breakdowns of democracy will be discussed.

Mode Types

- p-modes: trapped acoustic waves, high frequency
- g-modes: trapped gravity waves, low frequency
  - requires departure from adiabat, e.g., a composition gradient
- f-modes: "…can be regarded as the p- or g-mode without nodes…" (Unno et al.). Intermediate frequency. Periods ~100 minutes on Saturn
- inertial modes: Coriolis dominated oscillations

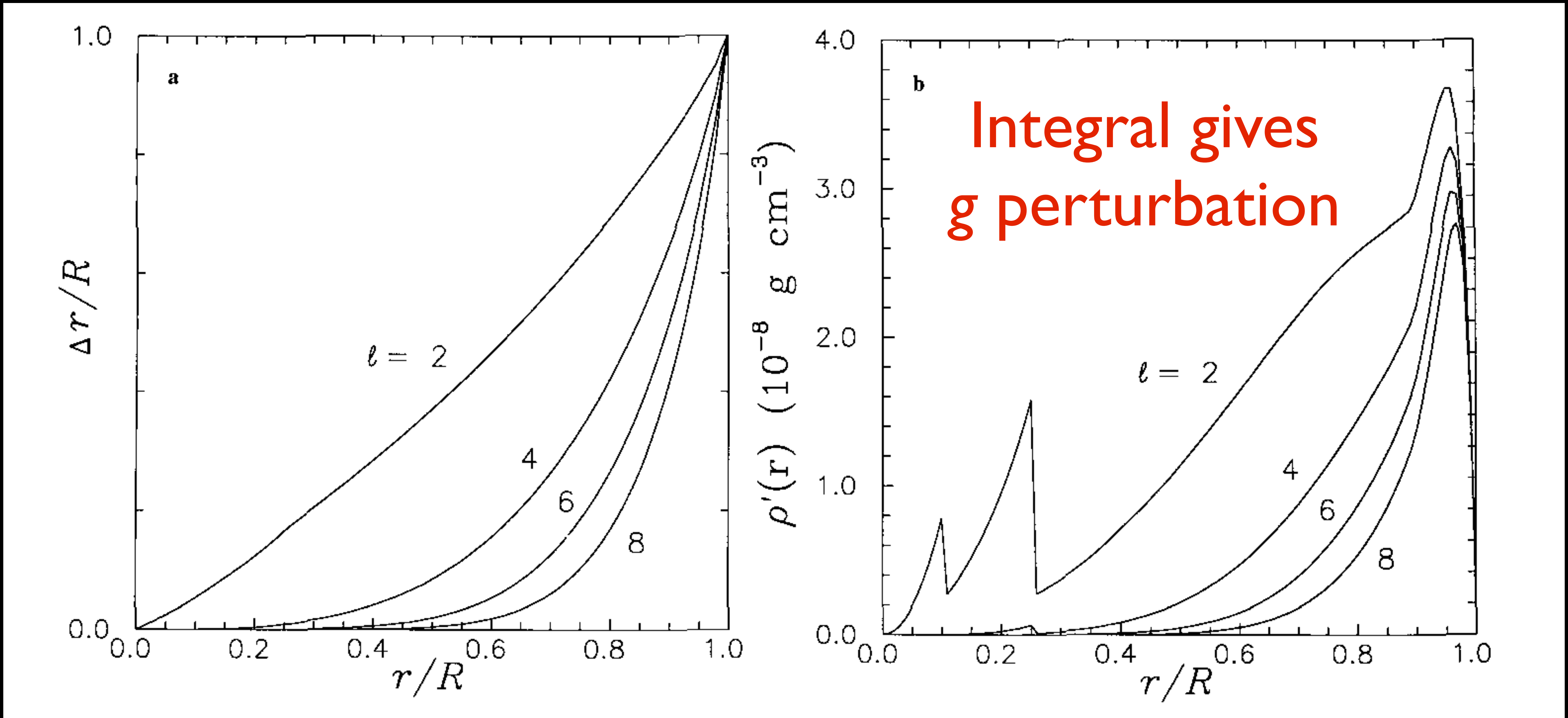
Subsequently

- Marley grad student LPL 1984-‘90
- Hubbard suggests possible thesis topics, mentions Stevenson idea
- Discards p-modes (radial nodes) & inertial modes (too difficult)
- But f-modes have correct periods & no radial nodes



Vorontsov & Zharkov (1981)

f-mode perturbations (no radial nodes)



Marley (1991)

f-mode

- For a spherical planet 1 mode couples to 1 ring perturbation by orthogonality of spherical harmonics

- Challenge in computing frequencies arises from oblate Saturn, coupling between modes, uncertain rotation profile with depth…

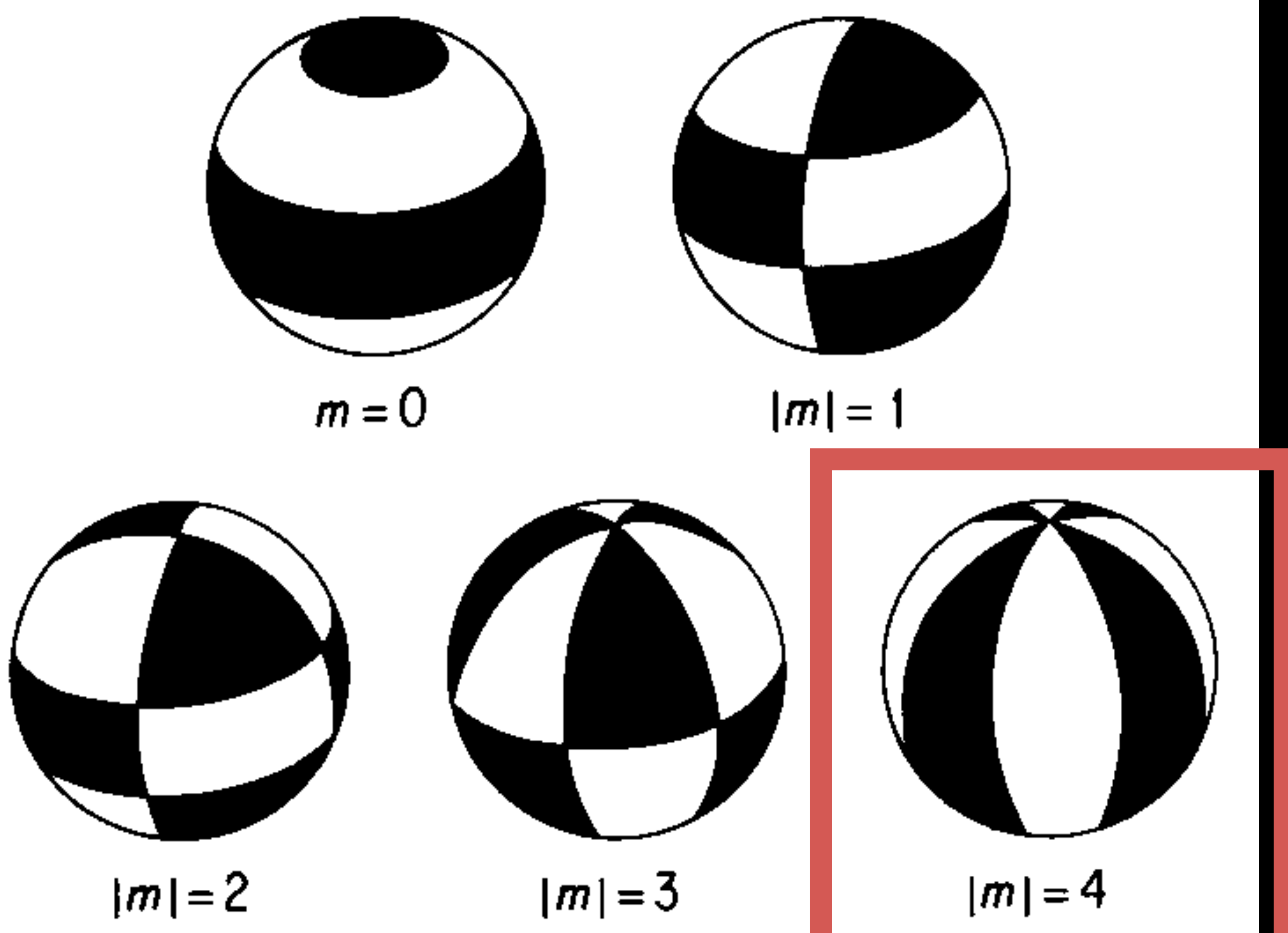
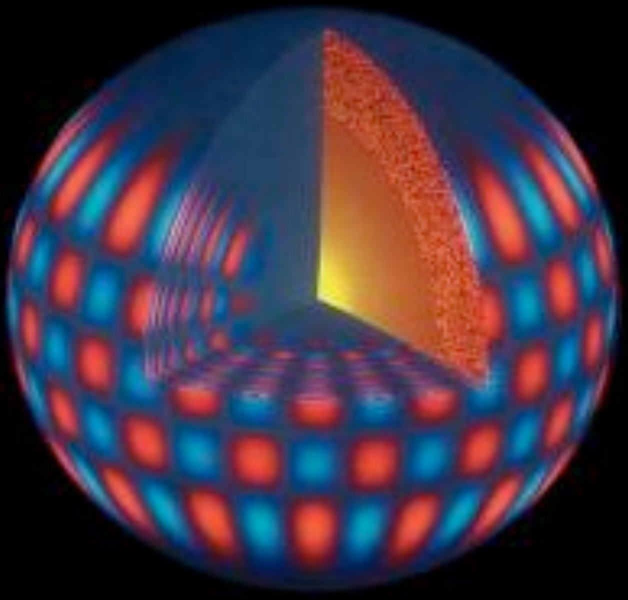
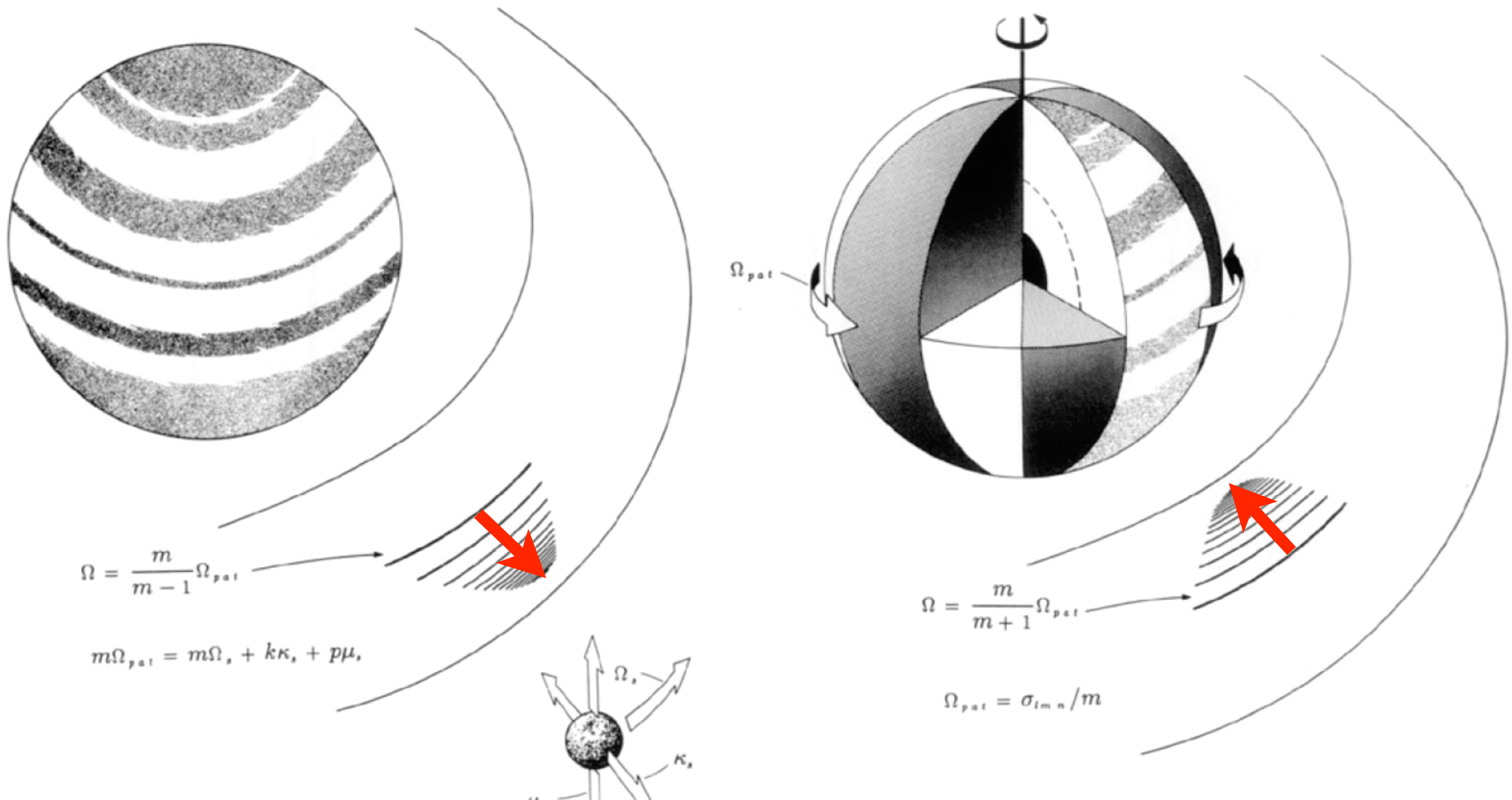


FIG. 1. Illustration of spherical harmonics for degree l = 4.



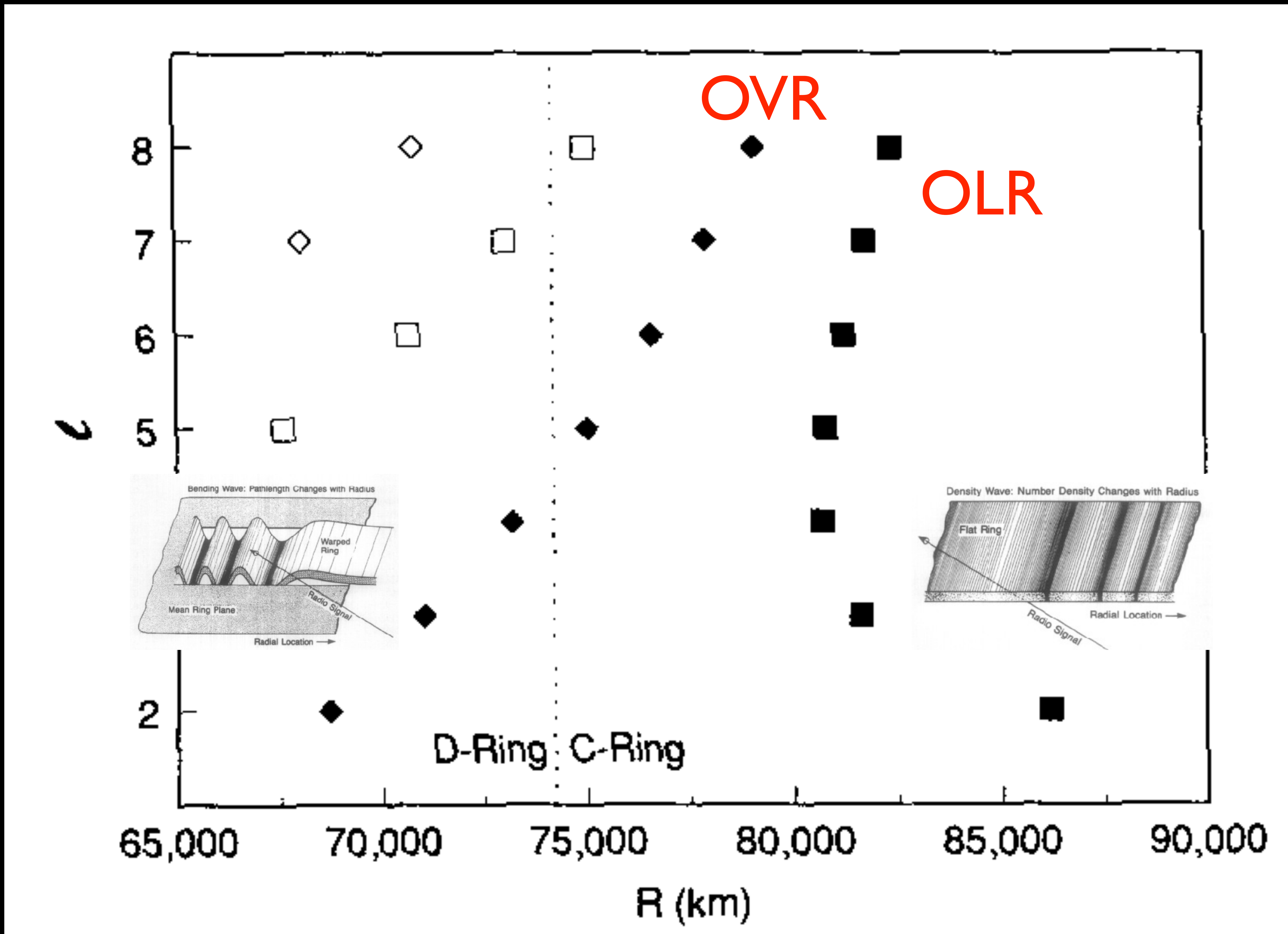


Marley & Porco (1993)

Marley & Porco (1993)

Theory of ring waves casts satellite gravity forcing in spherical harmonics, so fairly straightforward port of theory to oscillation gravity perturbations

Predicted Resonance Locations



Marley & Porco (1993)

Specific Predictions

TABLE I
Oscillation Mode Resonance Locations

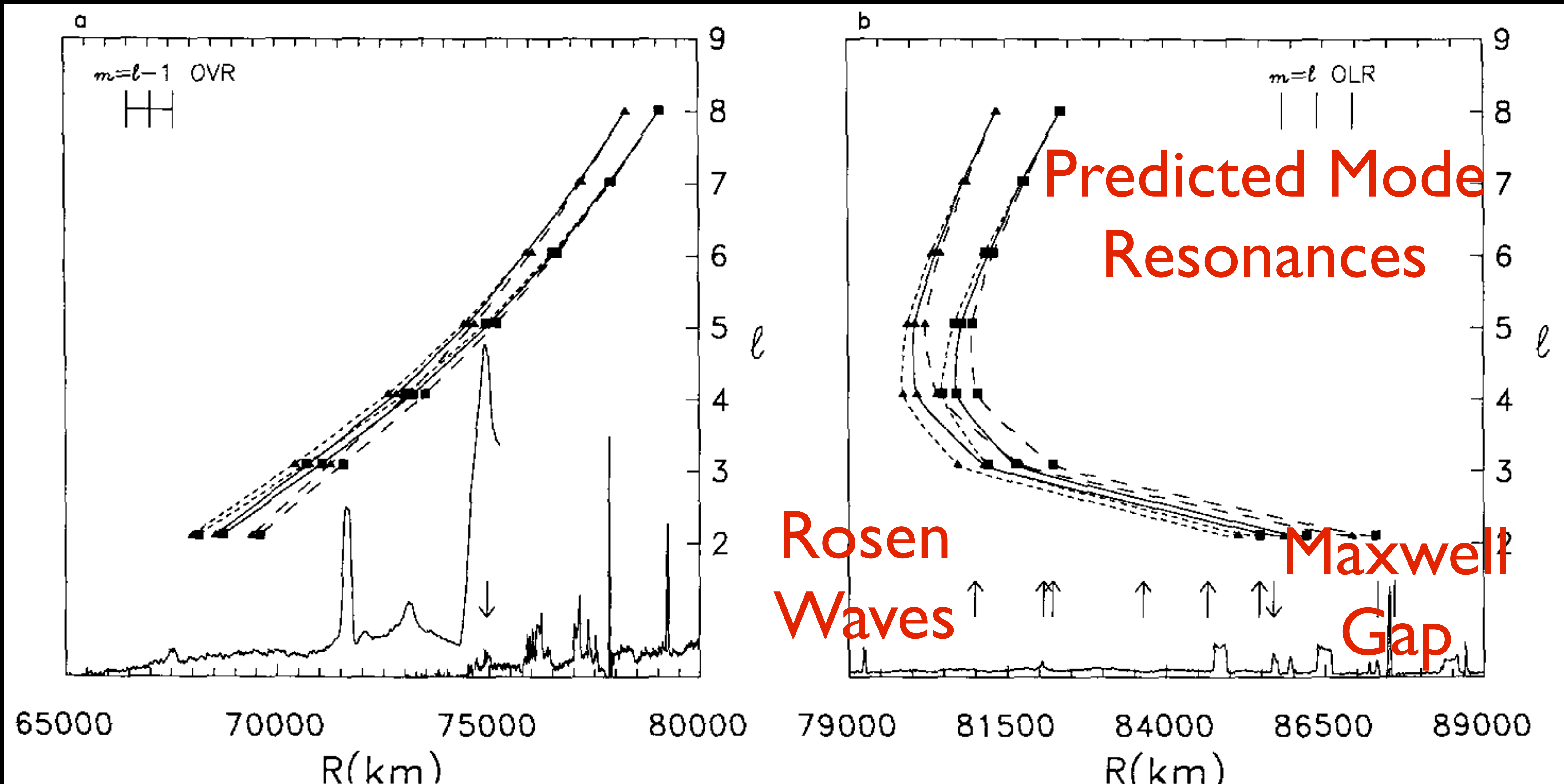
l	m	P_{planet} (min)	P_{pat} (min)	Type	R_{res} (km)	$T^*_{L,V}$[a] (10^{15} erg)	A_L (g cm^{-2}) or $\lvert A_V\rvert\Sigma^{1/2}$ (km $\sqrt{\text{g cm}^{-2}}$)
2	2	259.3	286.4	OLR	86,215	21.	[illegible]
	1	196.1	150.1	OVR	68,726	−1.3	[illegible]
3	3	184.2	296.4	OLR	81,640	9.1	4.7
	2	157.9	211.4	OVR	71,064	−0.49	2.3
4	4	151.0	310.6	OLR	80,714	3.8	2.7
	3	136.2	249.3	OVR	73,219	−0.17	1.2
5	5	131.2	323.4	OLR	80,799	1.5	1.9
	4	121.7	276.4	OVR	75,047	−0.057	0.6
	3	114.2	223.1	OLR	67,625	0.43	1.6
6	6	117.8	335.7	OLR	81,235	0.63	1.2
	5	111.0	297.2	OVR	76,600	−0.020	0.3
	4	105.5	254.2	OLR	70,696	0.20	1.0
7	7	107.7	344.4	OLR	81,760	0.22	0.7
	6	102.6	313.7	OVR	77,901	−0.0064	0.1
	5	98.39	278.1	OLR	73,039	0.078	0.6
	4	94.81	238.0	OVR	68,058	−0.0083	0.2
8	8	100.0	355.4	OLR	82,375	0.095	0.4
	7	96.05	327.7	OVR	79,082	−0.0024	0.08
	6	92.65	297.4	OLR	74,969	0.034	0.3
	5	89.71	263.6	OVR	70,809	−0.0032	0.1

[a] $T_{L,V} = T^*_{L,V} \cdot (\Sigma/1\ \text{g cm}^{-2}) \cdot \left(\frac{\Delta r_{1\,\text{bar}}}{100\ \text{cm}}\right)^2$.

Large torque

Marley & Porco (1993)

Uncertainties



Marley & Porco (1993)

TABLE IV
Possible Ring Associations

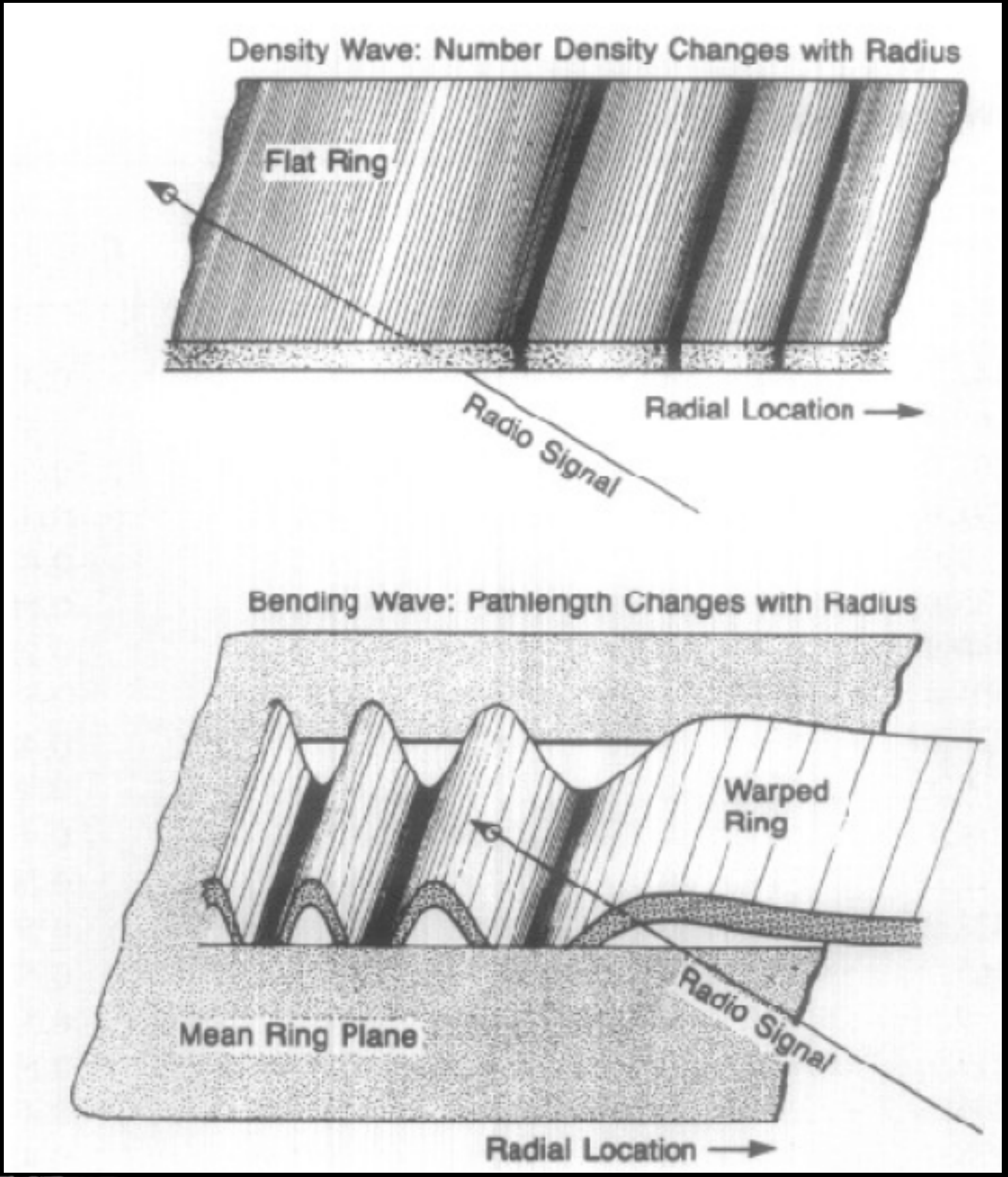
f-mode l, m	Location (km)	Feature type	m_{obs}[a]	Resonance type	$m_{predict}$	Consistent?
2, 2	87,400	Maxwell gap			2	Yes
2, 1	69,500	Wavelike feature	—	OVR	1	—
3, 3	82,211	OLR/IVR	2–5	OLR	3	Yes[b]
3, 3	82,065	OLR/IVR	2–4	OLR	3	Yes[b]
3, 2	71,695	D-ring feature	—	OVR	2	—
4, 4	80,990	OLR/IVR	3–11	OLR	4	Yes
4, 3	73,090	D-ring feature	—	OVR	3	—
5, 4	74,945	OVR/ILR	2–3	OVR	4	No

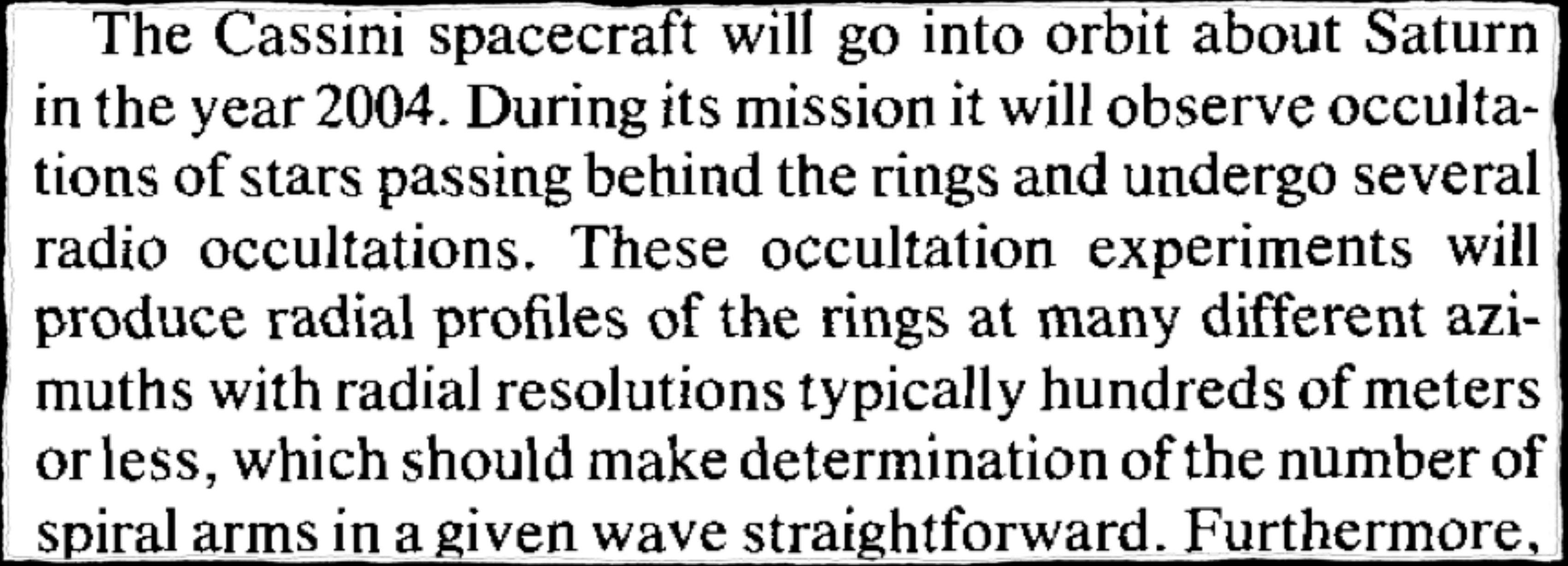
[a] Observed azimuthal wavenumber (Rosen *et al.* 1991a).
[b] $l = 3$, $m = 3$ f-mode would be associated with one of these two waves.

Marley & Porco (1993)

Tests

- Are waves IVR (satellite) or OLR (Saturn)? Bending or density?
- What is azimuthal wave number? *m* should agree with prediction

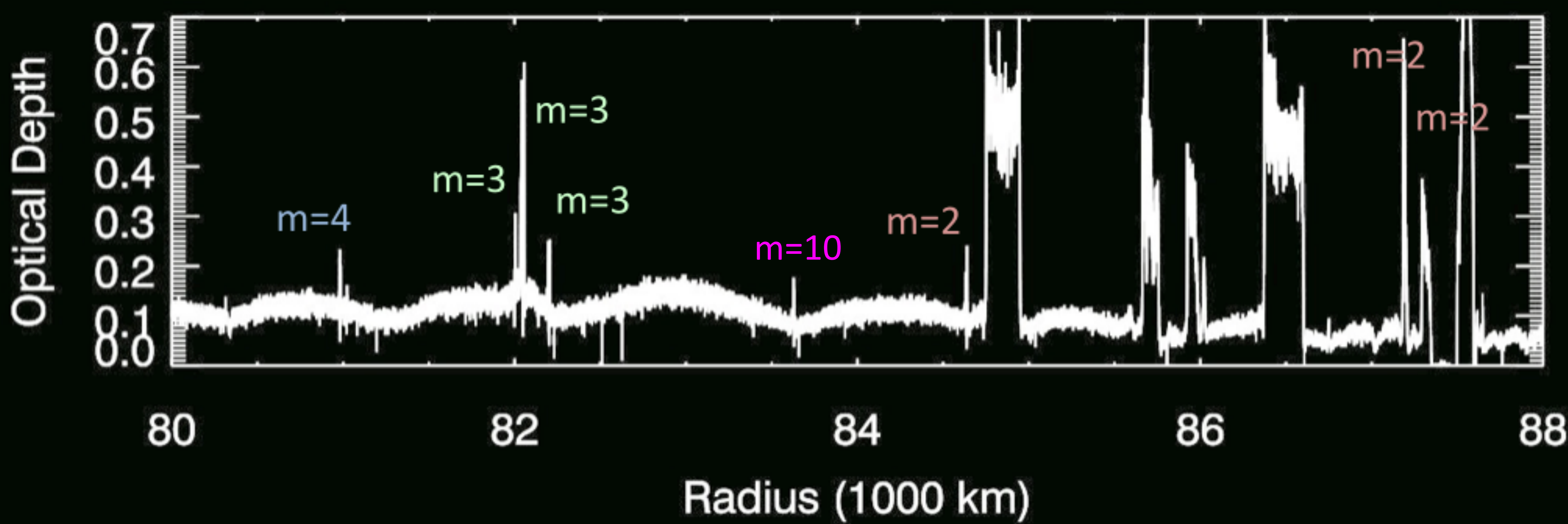



The Cassini spacecraft will go into orbit about Saturn in the year 2004. During its mission it will observe occultations of stars passing behind the rings and undergo several radio occultations. These occultation experiments will produce radial profiles of the rings at many different azimuths with radial resolutions typically hundreds of meters or less, which should make determination of the number of spiral arms in a given wave straightforward. Furthermore,

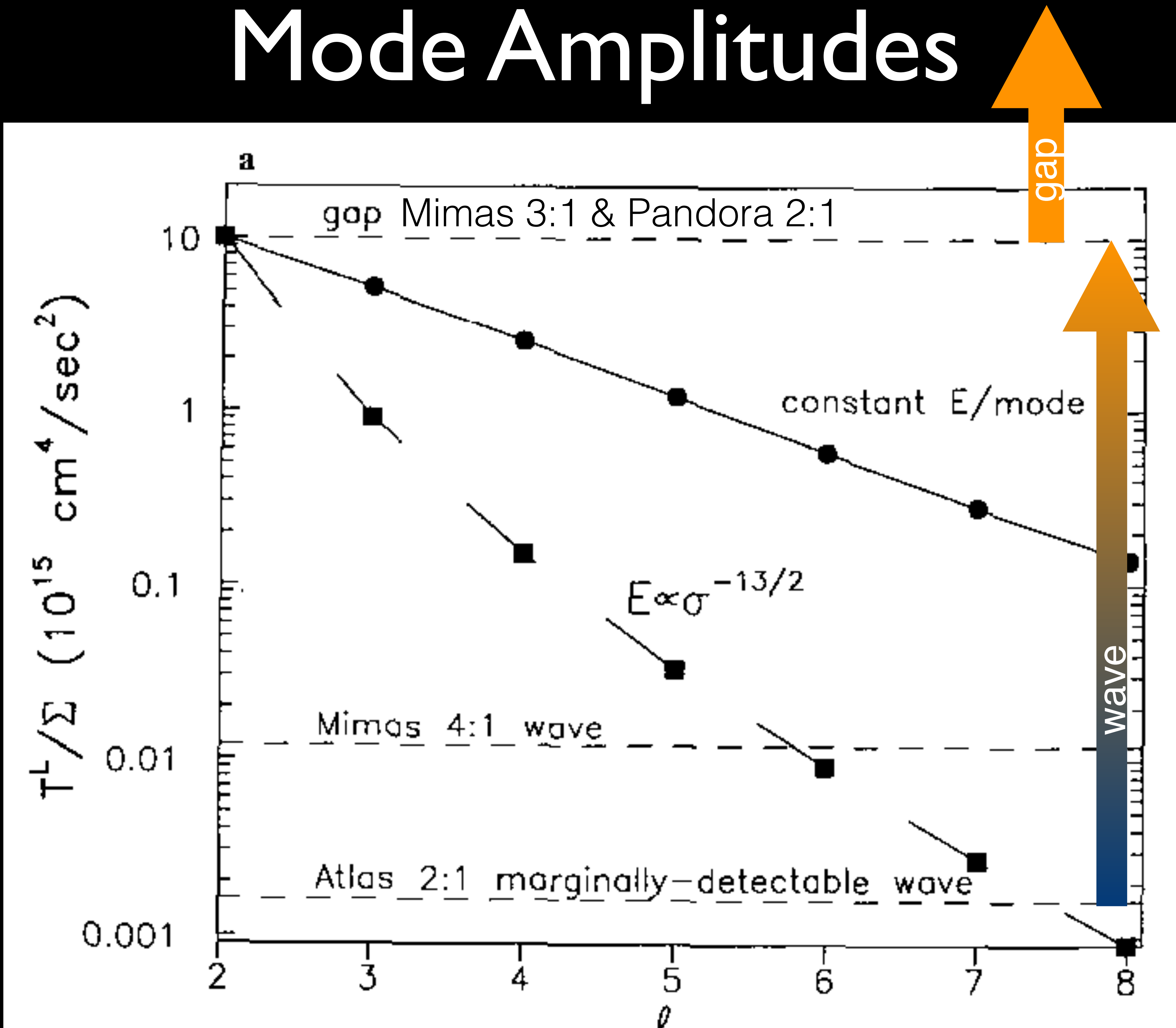
Marley & Porco (1993)

Hedman & Nicholson

- Waves are density waves excited at OLRs
- Additional frequency splitting beyond rotation
- Not all *m* are equally excited



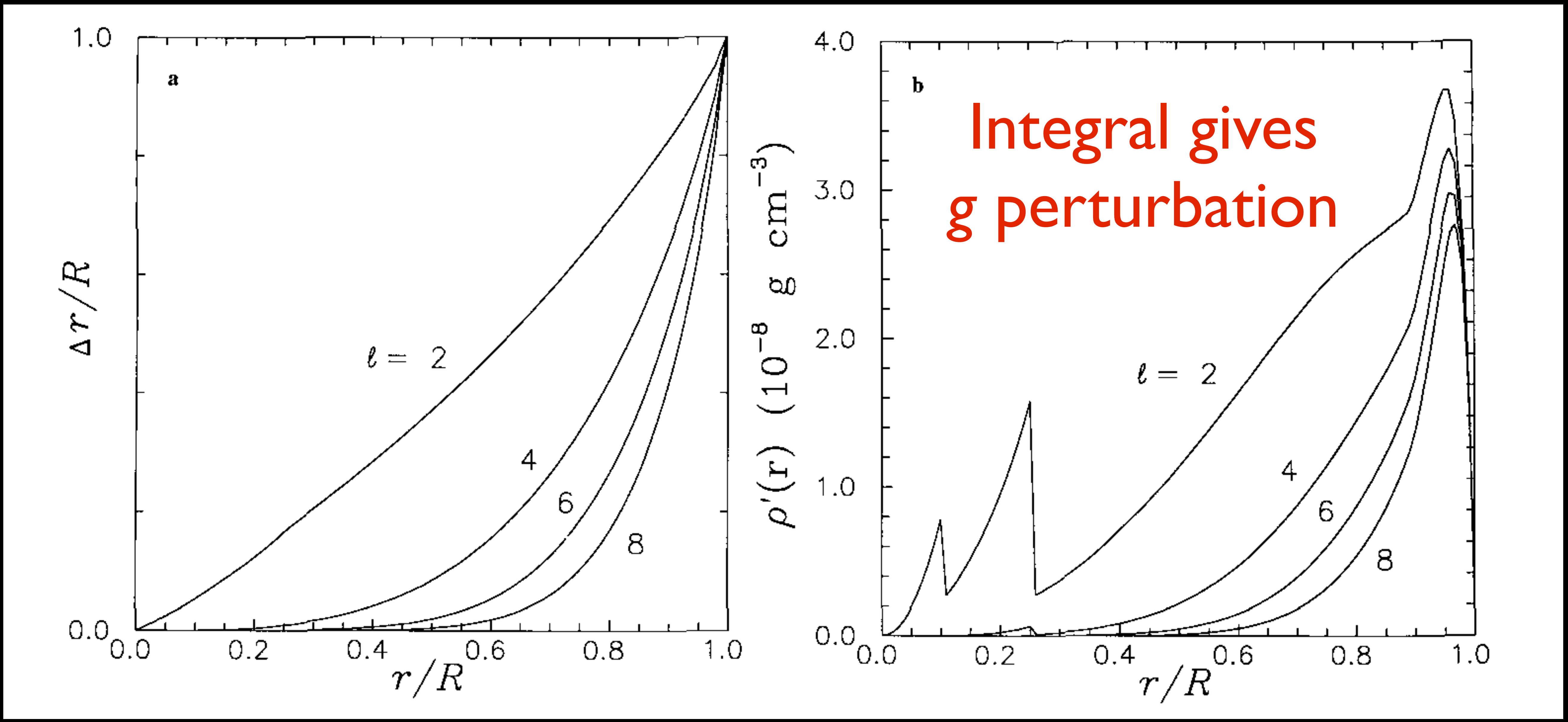
Mode Amplitudes



Marley & Porco (1993)

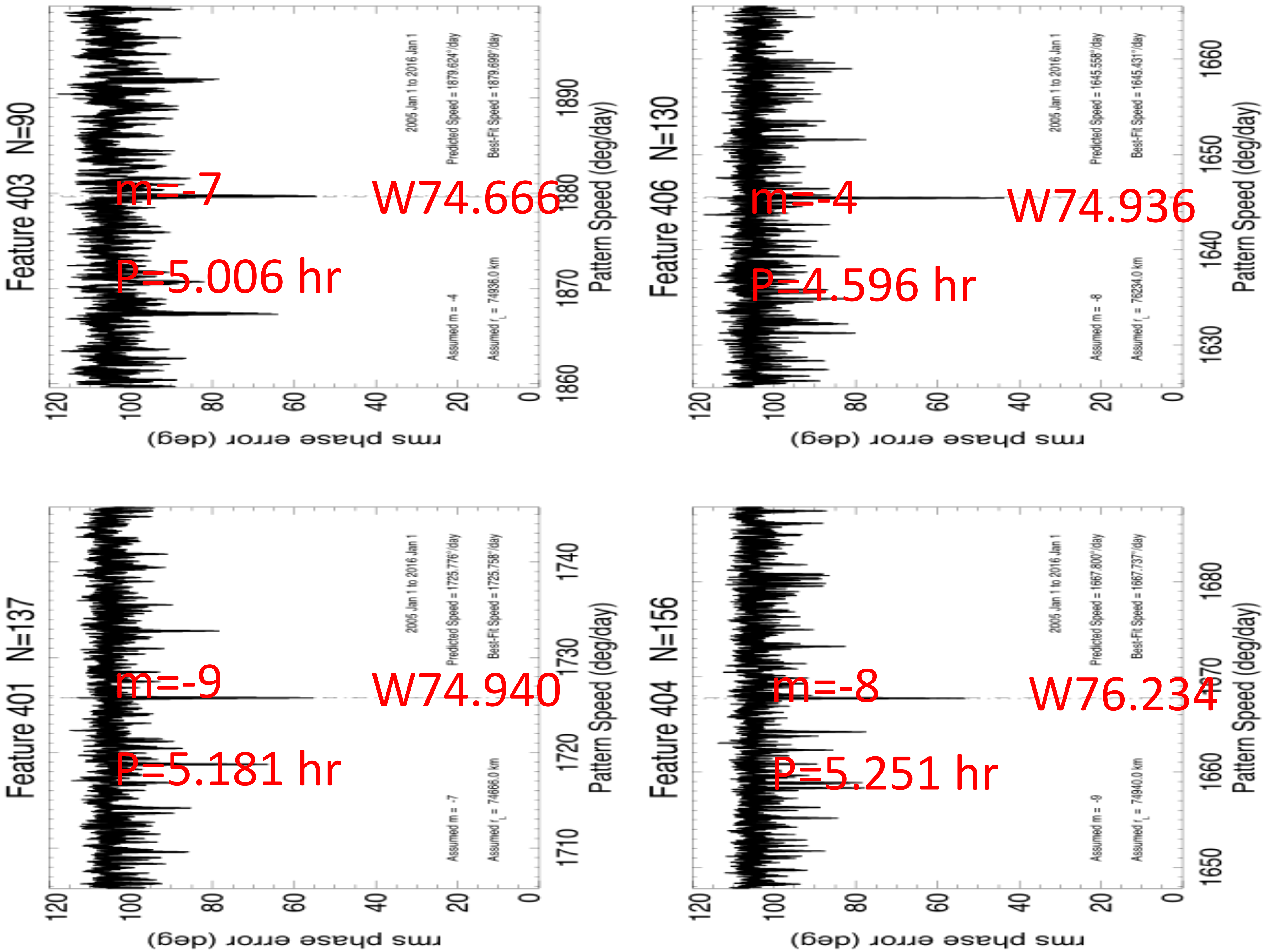
- mode amplitude translates to torque applied to rings
- few meter amplitudes can launch waves

f-mode perturbations
(no radial nodes)

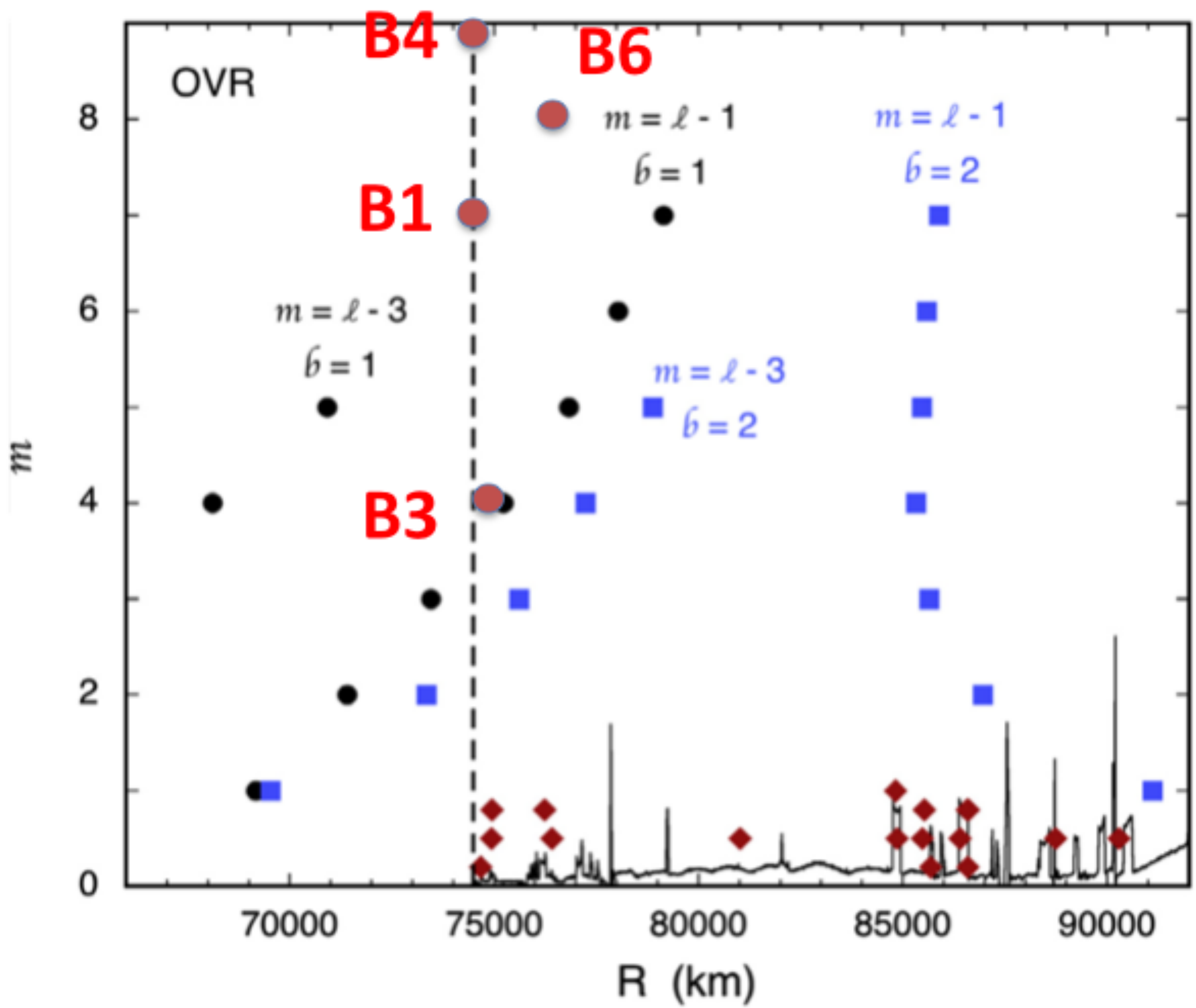


Marley (1991)

Four OVR bending waves in C ring



Four OVR Waves...



Summary

- ~10 wave features in rings associated with f-modes
- interpretation tricky because of ‘hyper fine’ splitting
- some modes show no such splitting, also detect m, m-1 for same degree mode, so rotational splitting measured
- characteristics of ring features bounds mode amplitudes
- ~few meter amplitudes can explain wave generation (~0.2 cm/s velocities)
- no excitation mechanism yet established