HST/STIS imaging of Fomalhaut: New main belt structure and confirmation of Fomalhaut b's eccentric orbit

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• Fomalhaut is a 2 solar mass, 440 Myr-old, A star at 7.7 pc
• Dusty debris belt at 140 AU radius mapped from optical to millimeter wavelengths.
• HST optical data with ACS/HRC revealed faint proper motion companion Fomalhaut b interior to the dust belt.
• Fomalhaut b may represent light reflected from a circumplanetary ring or irregular satellite dust swarm
• Not detected in IR -> mass is less than ~1 Jupiter
Fomalhaut b confirmed in HST data by two independent studies

New results

• Re-analysis of astrometry and error sources for 2004, 2006 ACS data, and 2010 STIS data.

• New Observations with HST/STIS obtained May 2012
  – 12 orbits, 12 roll angles
  – STIS coronagraphic wedge, blocks 2.5 arcsec
  – 0.05077”/pix, no filters, 0.2-1.0 micron
  – Use self-subtraction at multiple rolls, no PSF star
1. Fomalhaut b confirmed again in 2012

2. Fomalhaut b is real: Four HST papers from three independent research groups
Tracking Fomalhaut b for eight years with Hubble
Fomalhaut b’s highly eccentric orbit is confirmed

Astrometry on a single background star detected at all four epochs fits the expected parallax and proper motion trajectory relative to Fomalhaut.

Fomalhaut b

Background star
MCMC method developed by James Graham to sample the posterior probability distribution for the orbital elements based on 4 epochs of astrometry.

Sample of 100 orbits drawn from the Markov chains.
New estimate for the Fomalhaut b orbital elements.

- Semi-major axis: $a = 177 \pm 68$ AU [Main Belt ~ 140 AU]
- Eccentricity: $e = 0.8 \pm 0.1$ [Main Belt ~ 0.1]
- Perihelion: $q = 32 \pm 24$ AU, $Q = 322 \pm 119$ AU
- Inclination: $I = 17^\circ \pm 12^\circ$
- Orbital period: $P \sim 1700$ yr [Main Belt ~ 1100-1400 yr]

Is Fomalhaut b still dynamically related to the belt? Mutual Inclination

\[
\langle \delta i \rangle = 17.0 \pm 12.0^\circ
\]

50\textsuperscript{th}-\%	extsuperscript{ile} = 13.3^\circ; 90\textsuperscript{th}-\%	extsuperscript{ile} = 36.3^\circ
Is Fomalhaut b still dynamically related to the belt? Apsidal Alignment

\[ \omega_{\text{orbit}} = 178 \pm 18^\circ \]

\[ \omega_{\text{belt}} = 185^\circ \]
Belt Halo Detected in Northwest
(comparable southeast field not available)

Extended halo of dust out to 209 AU, possibly >276 AU with bending morphology

- Previous images detect a narrow belt 133-165 AU
- New data show the belt extends at least out to 209 AU radius
- Belt halo not linear – bends downward in image above

Take home point: Belt has perturbed structure at large distances from star
Kalas, Graham, Fitzgerald, & Clampin, IAU 299, 06/2013

Discovery of Main Belt Gap

Not totally empty, FWHM=50 AU

Sketch of the Fomalhaut system based on observations
What accounts for Fomalhaut b’s high eccentricity?
Multi-planet system: Was Fomalhaut b scattered in, or out?
Fomalhaut b’s orbit is similar to a minority of Centaurs, such as 2010 TR19, which enters into our planetary system (crosses Neptune’s orbit) on a very elliptical orbit.

Implication:
(1) Fomalhaut b has a short-lived orbital configuration.
(2) Fomalhaut b is very low-mass.
**Fomalhaut b is a low-mass, Centaur-like object?**

**Question:** How massive does a central object have to be so that an 30 $R_J$ (0.014 AU) radius cloud is not disrupted by tidal shearing at periapse?

**Answer:** $5 \times 10^{21}$ kg

Mass of dust required consistent with a single cratering impact on the dwarf planet.

Numerical model (Kalas et al. 2013)
Fomalhaut b is a planet that was scattered out?

Example from Chatterjee et al. 2008

- Simulate 3-planet systems, variety of mass ratios, inclinations, separations
- Massive planets eject lesser mass planets.
- Mutual inclinations change
- Planet with outer final orbit tends to have higher eccentricity.
Does Fomalhaut b disrupt the belt if coplanar?
Belt edges erode, timescale depends on mass

- Neptune mass after 300 kyr
- Saturn after 75 kyr
Nested coplanar Jupiter + Eccentric NON-coplanar Neptune

http://www.youtube.com/watch?v=kD9t2vAo3uQ
Take home points

• Fomalhaut b is real
Summary

• The Fomalhaut b orbit after 8 years of HST imaging:
  – Eccentric: $e = 0.8 \pm 0.1$
  – “Belt crossing” *in projection*
  – Periastron at $32 \pm 24$ AU
  – Mutual inclination w.r.t. belt $< 36^\circ$

• Minimum mass is a dwarf planet, maximum is $\sim 1 \, M_j$

• The belt survives planet crossings, but new features unexplained.

• Open questions: Was it scattered in or scattered out? What is the relationship to the belt? Where are the other planets, if any?
Future Observations

- With HST, refine Fomalhaut b’s orbit, as well as photometry and morphology. Build SNR on the belt to map substructure.

- With ground-based telescopes, use ALMA to map the dust in the system, and adaptive optics to search for Fomalhaut c.

- Theory: Understand the dynamical history of the Fomalhaut system, providing an improved understanding of our own solar system’s early evolution.

- Around 2032, Fomalhaut b may begin crossing through the main belt, producing new phenomena.