RADAR OBSERVATIONS OF SEVEN X/M-CLASS MAIN-BELT ASTEROIDS. M. K. Shepard[1], P. A. Taylor[2], M. C. Nolan[2], E. S. Howell[2], L.A.M. Benner[3], J.D. Giorgini[3], B. D. Warner[4,5], A. W. Harris[4], B.E.Clark[6], M. Ockert-Bell[6], D. Coley[7]. [1]Department of Geography and Geosciences, Bloomsburg University, Bloomsburg, PA 17815, mshepard@bloomu.edu, [2]Arecibo Observatory, NAIC, Arecibo, PR 00612, [3]Jet Propulsion Laboratory, Pasadena, CA 91109, [4]Space Science Institute, La Cañada, CA 91011, [5]Palmer Divide Observatory, Colorado Springs, CO 80908. [6]Ithaca College, Ithaca, NY 14853, [7]Center for Solar System Studies, Rancho Cucamonga, CA 91730.

Introduction: Using the S-band (12.6 cm) radar system at Arecibo Observatory, we observed the following X/M-class main-belt asteroids (MBAs) in November and December 2011: 77 Frigga, 92 Undina, 201 Penelope, 261 Prymno, 413 Edburga, 441 Bathilde, and 678 Fredegundis. Our objective was to determine the radar albedo of these objects and, by inference, their metal content [1].

The M-class asteroids are defined [2] as moderate visual albedo objects ($0.1 \leq p_v \leq 0.3$) with featureless, red-sloped visible/near-infrared spectra. Traditionally, they have been thought to be either the denuded metal cores of ancient planetesimals or enstatite chondrites [3] [4]. Because iron-nickel, the presumed composition of planetesimal cores, is much denser than silicates, radar echoes are diagnostic of metal abundance [1] and can be used to distinguish between these and other proposed compositional scenarios. Including these asteroids, we have now observed a total of 26 X/M-class MBAs with radar.

Methods: We transmit a continuous-wave (CW) radar beam to the asteroid for round-trip light travel time to the target and then receive the echo for a similar duration in both same (SC) and opposite (OC) circular senses of the transmission polarization. Each transmit/receive cycle is one "run." The OC radar albedo of each target, a value between 0 and 1.0, is estimated by integrating the entire echo power spectrum and ratioing it to that expected from a perfect metallic sphere of the same cross-sectional area at the same distance. Higher values indicate higher near-surface bulk densities. Using empirical data, Shepard et al. [1] estimate that radar albedos of ~0.4 or higher in MBAs are indicative of near surfaces dominated by metal.

Results: We summarize results for each asteroid.

77 Frigga. We obtained one run on 17 Dec. 2011. More runs are expected in Jan 2012. Preliminary results indicate a radar albeo of 0.20 ± 0.07, inconsistent with a metal-dominated surface of expected bulk porosity.

92 Undina. We obtained four runs between 11-14 Nov. 2011. Our results indicate a mean radar albedo of 0.36 ± 0.08 with a rotation-dependent range of 0.27-0.44. This suggests a metal-dominated composition and the variations with rotation are consistent with other high radar albedo targets [1]. Undina's echo is bimodal, suggesting a bifurcated or contact-binary structure. Undina is also a Rivkin "W" class [5], defined as an X/M-class asteroid with a 3-micron absorption feature interpreted to be caused by hydrated minerals. It is commonly assumed that high-metal asteroids and hydrated minerals are incompatible because of different formation conditions (i.e. high vs. low temperature of formation).

201 Penelope. We obtained two runs on 11 and 14 Nov. 2011. Preliminary results indicate a radar albedo of 0.55 ± 0.10, strongly suggesting a composition dominated by metal. Penelope's echo is also bimodal, suggesting a bifurcated or contact-binary structure. This had been suggested previously based on lightcurve behavior [6]. Penelope is also a "W" class.

261 Prymno. We obtained four runs between 19 Nov. and 16 Dec. 2011. We measured a mean radar albedo of 0.23 ± 0.06, inconsistent with a composition dominated by metal.

413 Edburga. We obtained three runs between 12-14 Nov. 2011. We measured a radar albedo of 0.35 ± 0.08, significantly higher than the mean for MBAs and indicative of a significant metal content. Edburga's echo is also bimodal, suggesting a bifurcated or contact-binary structure.

441 Bathilde. We obtained three runs between 17-18 Dec 2011. We measured a mean radar albedo of 0.20 ± 0.05, inconsistent with a metal surface.

678 Fredegundis. We obtained four runs between 16-18 Dec. 2011. Previous radar observations of Fredegundis in Jan. 2008 [1] led to a radar albedo estimate of 0.18 ± 0.05 and showed evidence for a bifurcated structure. Our more recent results are consistent with these. We measured a radar albedo of 0.16 ± 0.04 and found additional evidence for a bifurcated structure.

Significant Findings: Of the 26 X/M-class MBAs observed by radar, 11 (about 40%) have high radar albedos consistent with a surface composition dominated by metal. The remainder have radar albedos considerably higher than the mean MBA [7], suggesting a higher than "typical" metal content.

We have now observed four W-class asteroids, those with 3-micron absorption features often attributed to hydrated minerals, with metal-like high radar albedos: 92 Undina, 129 Antigone [8], 201 Penelope,

and 413 Edburga (ESH, unpublished data). This requires either a re-evaluation of the cause of the 3-micron feature or of our fundamental assumptions about the nature of these asteroid surfaces.

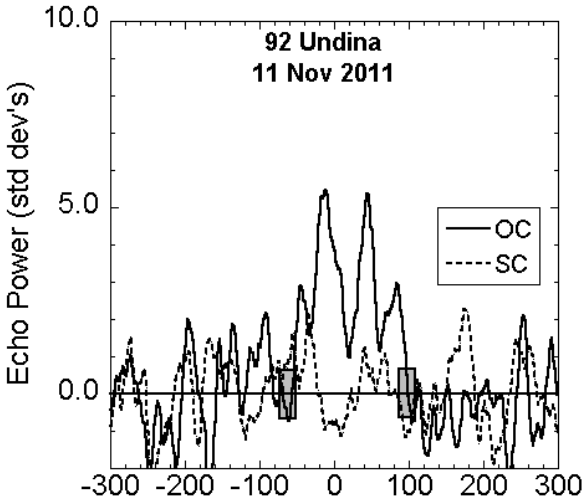

Fig. 1. Smoothed CW spectra of 92 Undina illustrating a bifurcated OC echo.

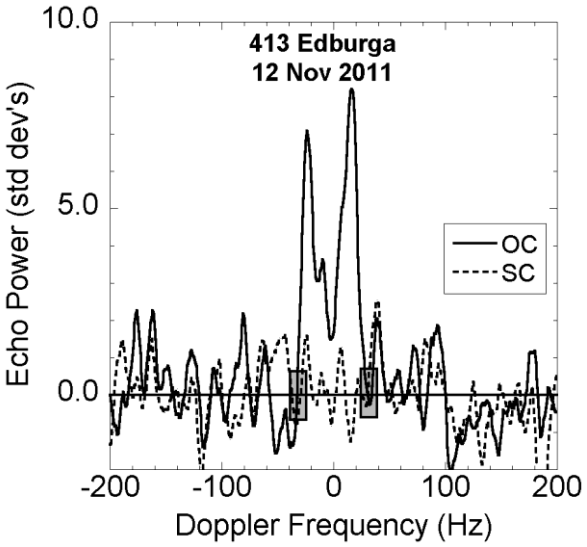

Fig. 2. Smoothed CW spectrum of 413 Edburga.

Including those asteroids observed in previous work, the following radar-observed X/M-class MBAs are multiples, bifurcated, or show strong evidence for bifurcation in their radar echo power spectra: 22 Kalliope [9], 92 Undina, 110 Lydia [1], 129 Antigone [8], 201 Penelope, 216 Kleopatra [10], 413 Edburga, 678 Fredegundis [1], 758 Mancunia [1], and 779 Nina [1]. Of the remaining X/M-class asteroids observed, a significant number do not have sufficient rotational coverage to make this assessment, so there could be more. Thus another significant conclusion is that 40% of the X/M-class radar targets, including many high albedo objects, show evidence of multiple or bifurcated systems (Figs. 1-3).

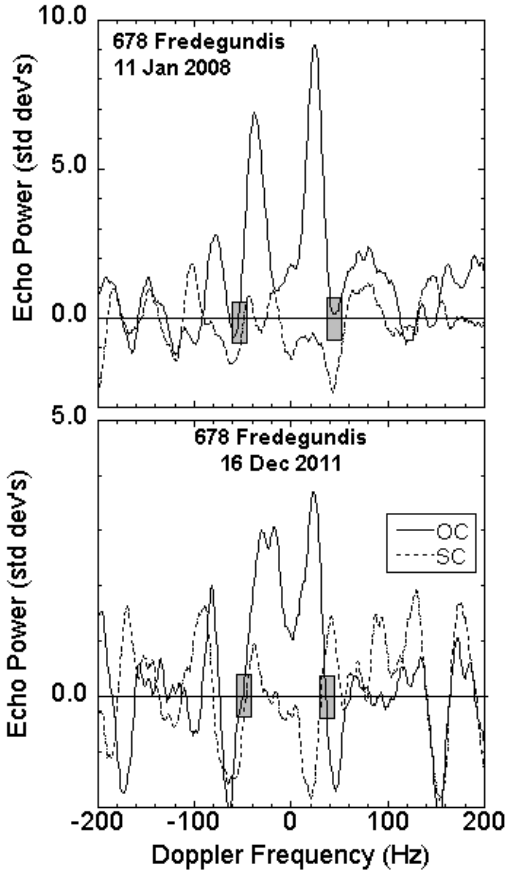

Fig 3. 2008 and 2011 spectra of 678 Fredegundis.

References: [1] Shepard et al. (2010) *Icarus, 208,* 221-237. [2] Tholen D. (1984) *Ph.D. Thesis, U.of Arizona, Tuscon.* [3] Bell et al. (1989) in Asteroids II, 921-948. [4] Gaffey (1976) *J.Geophys. Res*, 81, 905-920. [5] Rivkin et al. (2000) *Icarus*, *145*, 351-368. [6] Torppa et al. (2003) *Icarus 164*, 346-383. [7] Magri et al. (2007) *Icarus 186*, 126-151. [8] Shepard et al. (2008) *Icarus 195*, 184-205. [9] Margot and Brown (2003) *Science 300*, 1939-1942. [10] Ostro et al. (*2000) Science 288*, 836-839.

Acknowledgments: MKS and BEC acknowledge support from NSF AST-0908098 and 0908217. AWH and BDW acknowledge support from NASA NNG-06G132G and NSF AST-0607505. Arecibo Observatory is operated by SRI Int. under a cooperative agreement with NSF and in alliance with Ana G.Mendez-Univ. Metropolitana and USRA. We thank the Arecibo operators and staff for their help in observing.