Icarus 200 (2009) 129–146

Contents lists available at ScienceDirect

Icarus

www.elsevier.com/locate/icarus

Elemental composition of 433 Eros: New calibration of the NEAR-Shoemaker XRS data

Lucy F. Lim[a,*], Larry R. Nittler[b]

[a] Code 691, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
[b] Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington, DC 20015, USA

ARTICLE INFO

Article history:
Received 9 October 2007
Revised 12 September 2008
Accepted 21 September 2008
Available online 18 November 2008

Keywords:
Asteroid Eros
Asteroids, composition
Asteroids, surfaces
Asteroids

ABSTRACT

We present a new calibration of the elemental-abundance data for Asteroid 433 Eros taken by the X-ray spectrometer (XRS) aboard the NEAR-Shoemaker spacecraft. (NEAR is an acronym for "Near-Earth Asteroid Rendezvous.") Quantification of the asteroid surface elemental abundance ratios depends critically on accurate knowledge of the incident solar X-ray spectrum, which was monitored simultaneously with asteroid observations. Previously published results suffered from incompletely characterized systematic uncertainties due to an imperfect ground calibration of the NEAR gas solar monitor. The solar monitor response function and associated uncertainties have now been characterized by cross-calibration of a large sample of NEAR solar monitor flight data against contemporary broadband solar X-ray data from the Earth-orbiting GOES-8 (Geostationary Operational Environmental Satellite). The results have been used to analyze XRS spectra acquired from Eros during eight major solar flares (including three that have not previously been reported). The end product of this analysis is a revised set of Eros surface elemental abundance ratios with new error estimates that more accurately reflect the remaining uncertainties in the solar flare spectra: $\mathrm{Mg/Si} = 0.753 + 0.078/{-0.055}$, $\mathrm{Al/Si} = 0.069 \pm 0.055$, $\mathrm{S/Si} = 0.005 \pm 0.008$, $\mathrm{Ca/Si} = 0.060 + 0.023/{-0.024}$, and $\mathrm{Fe/Si} = 1.678 + 0.338/{-0.320}$. These revised abundance ratios are consistent within cited uncertainties with the results of Nittler et al. [Nittler, L.R., and 14 colleagues, 2001. Meteorit. Planet. Sci. 36, 1673–1695] and thus support the prior conclusions that 433 Eros has a major-element composition similar to ordinary chondrites with the exception of a strong depletion in sulfur, most likely caused by space weathering.

1. Introduction

The Near Earth Asteroid Rendezvous (NEAR)-Shoemaker spacecraft orbited the Asteroid 433 Eros between February 2000 and February 2001. Among its mission objectives (Cheng, 1997) was the characterization of the surface composition of Eros using X-ray (XRS, Goldsten et al., 1997) and gamma-ray spectrometers (GRS, Goldsten et al., 1997). XRS results were published during and immediately after the mission by Trombka et al. (2000) and Nittler et al. (2001), but were plagued by systematic uncertainties stemming from the unlucky failure of one solar monitor and the incomplete pre-launch calibration of the other. This paper describes the subsequent effort at post-launch calibration of the NEAR gas solar monitor and the resulting improvement in our understanding of the XRS-derived elemental composition of 433 Eros.

The X-ray fluorescence emission measured by NEAR is a product of the interaction of solar X-rays with the asteroid's surface. As the asteroid is exposed to X-rays from the upper solar atmosphere, a fraction of the incident X-rays is photoelectrically absorbed by various inner electron shells of atoms in the surface, resulting in the emission of either an Auger electron or a fluorescent X-ray, with energies characteristic (Moseley, 1913) of the atoms that produce them.

Each electron shell can only be induced to fluoresce by that portion of the solar X-ray spectrum that falls above its binding energy. Moreover, fluorescent X-rays emitted by one atom may be absorbed by another atom in the asteroid's surface prior to escape into space. The resulting spectrum of fluorescent lines depends both on the abundance of each element in the asteroid's surface and on the spectral distribution of the incident X-rays. Accurate knowledge of the incident solar spectrum is thus critical to converting the spectra received by the NEAR XRS into elemental abundances on the asteroid's surface.

NEAR, therefore, carried two X-ray spectrometers dedicated to monitoring the solar spectrum between 1 and 10 keV. One of these, a Si PIN photodiode, failed prior to orbit insertion. The second consisted of a gas-filled proportional counter similar to the

---

[*] Corresponding author.
E-mail addresses: lucy.f.lim@nasa.gov (L.F. Lim), lnittler@ciw.edu (L.R. Nittler).

0019-1035/$ – see front matter Published by Elsevier Inc.
doi:10.1016/j.icarus.2008.09.018

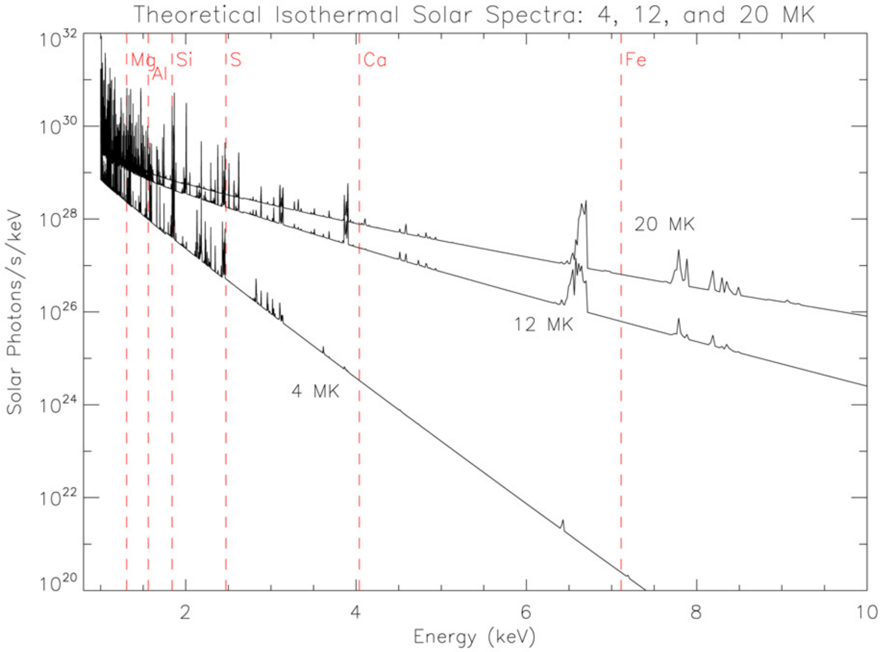

Fig. 1. Theoretical (CHIANTI 5.2; Dere et al., 1997; Landi et al., 2006) single-temperature solar spectra at three plasma temperatures. Vertical dashed lines represent the K edge energies of major elements measured by the NEAR XRS.

asteroid-pointing detectors, but covered by a graded filter (Clark et al., 1995) designed to attenuate the incoming solar flux and increase the dynamic range of the detector. Unfortunately, the response of this filter, particularly at off-normal solar incidence angles, was not adequately determined in the laboratory prior to launch.

This paper describes the post-launch calibration of the NEAR gas solar monitor and its application to the analysis of XRS spectra of 433 Eros acquired during eight major solar flares. The response of the graded filter and the uncertainties therein were modeled based on measurements and tolerances as recorded in the engineering diagrams. Resulting models of the gas solar monitor's response function were tested against flight data and checked against contemporaneous broadband X-ray data from the Earth-orbiting GOES-8 (Geostationary Operational Environmental Satellite) to reduce the range of possible solar monitor response functions to those that were consistent with the available data. Finally, the improved solar results were used to analyze data from eight major solar flares from which asteroid fluorescence was recorded by NEAR, resulting in a recalibrated elemental composition for 433 Eros. The remaining uncertainties in the solar spectra were incorporated into the error analysis for the asteroid's composition.

2. The solar X-ray spectrum

The solar X-ray output has been observed by instruments aboard a number of Earth-orbiting satellites. These have included various GOES (Geostationary Operation Environmental Satellites) broadband detectors; the SMM Bent Crystal Spectrometer (Acton et al., 1980) in the 1980s (1980, then 1984–1989); and the YOHKOH BCS and SXT (Bragg Crystal Spectrometer and Soft X-ray Telescope; Yoshimori et al., 1991) in the 1990s. After the NEAR mission, solar X-ray observations have also been conducted by the CORONAS-F X-ray spectrometer (RESIK; Sylwester et al., 2005) operated from 2001–2003, and RHESSI (Reuven Ramaty High-Energy Solar Spectroscopic Imager; Lin et al., 2002), launched in 2002.

The solar X-ray spectrum consists of a set of emission lines superimposed on a continuum. Emission lines in the region observed by NEAR (1–10 keV) come from highly ionized atoms (H and He-like electron shells). The continuum is produced by bremsstrahlung emission, primarily from hydrogen, and declines steeply with increasing energy. Both the slope of the bremsstrahlung continuum and the intensities of the various emission lines vary greatly with electron temperature (Fig. 1). Electron temperatures (T_e) in the corona generally are in the range ~2–30 × 10^6 K (e.g., Phillips, 2004), with the highest temperatures being reached only during major solar flares.

The amount of material at a given T_e is described by the "emission measure" (EM):

$$\mathrm{EM} \equiv \int n^2\, dV, \tag{1}$$

where n represents the plasma density and V is the volume of the hot plasma. The total spectrum for an isothermal plasma, then, is:

$$\phi_{\mathrm{emitted}}(\lambda, T_e) = \big(E_{\mathrm{ff}}(\lambda, T_e) + E_{\mathrm{fb}}(\lambda, T_e)\big) \int n_e^2\, dV \tag{2}$$

(Garcia, 1994), where E_{fb} is the emission line spectrum and E_{ff} is the bremsstrahlung continuum.

Generally, however, the solar spectrum is multithermal (e.g., Feldman et al., 1995; McTiernan et al., 1999). The thermal portion of the solar X-ray spectrum, then, can be represented by the integral over all temperatures of the amount of plasma at a given temperature (known as the "differential emission measure," DEM(T)) multiplied by the spectrum appropriate to that temperature:

$$\phi_{\mathrm{total}}(\lambda) = \int \phi(\lambda, T) \times \mathrm{DEM}(T)\, dT. \tag{3}$$

Typically, DEM(T) is calculated by observing the relative intensities of lines in the solar spectrum, since different species of ions have different emitting efficiencies as functions of temperature.

Because the NEAR gas solar monitor could not resolve individual spectral lines, its spectra do not contain enough information to permit full inversions of DEM(T). The typical structure of the DEM(T) of a solar flare represents two plasma components, one emitting at 5–10 MK and a hotter component emitting at 16–