Chapter 7

Conclusion and future works

7.1 Conclusions

7.1.1 This work increases the number of NEAs with measured sizes and albedos by 54%

Overall, we have obtained radiometric diameters and albedos for thirty-two NEAs. Seven of them where observed under different observing geometries and with different instruments.

This work increments the number of NEAs with measured sizes and albedos by 54%. If we include objects for which the diameter and the albedo have been refined, this increment increases to almost 70%.

We have mainly contributed to the physical characterization of objects smaller than 1 kilometer. There were very few thermal infrared observations of asteroids in this size range, and we have more than doubled the number of subkilometer-NEAs with measured size and albedos.

We have derived the surface color temperature of 16 NEAs. This is twice the number of objects for which this information was available before. The variation of the color temperature with phase angle gives insight into the surface thermal properties of asteroids and the phase angle spanned by our observations is very broad: from 3 to 93°.

In all these respects, we have contributed to build the largest database of radiometric observations of NEAs. Following results are obtained from these measurements.

7.1.2 The observed NEAs are on average brighter than main belt asteroids

The mean albedo of NEAs with reliable radiometric measurements is 0.27, which is much higher than the mean albedo of observed main-belt asteroids (~0.11).

S-type NEAs are on average 20% brighter than S-type MBAs, while C-types NEAs have on average albedos 57% higher than C-type MBAs.

We confirm, therefore, the evidence that NEAs and small asteroids in general have a different albedo distribution than larger main-belt asteroids.

Studies of the albedos derived by IRAS had shown how the albedo distribution of main-belt asteroids smaller than 50 km has different properties than the one of larger bodies (i.e. the mean albedo increases with decreasing diameter and the clear separation between C-type and S-type asteroids vanishes at the smaller sizes. Such dichotomy between the albedo statistics of large and small asteroids is confirmed by our findings.

This implies a fundamental difference in surface properties of small asteroids with respect to the larger ones.

With our statistics we can improve the estimation of the albedo (and size, given the H value) for those NEAs for which taxonomic type is known.

7.1.3 There is a trend of increasing albedo with decreasing size for observed S-type NEAs

If real, the trend of increasing albedo with decreasing size may be indicative, for instance, of recently exposed, relatively unweathered surfaces.

This result is also consistent with the trend to ordinary-chondrite-type reflection spectra with decreasing size observed in the NEA population, which is also attributed to a lack of space weathering of relatively young surfaces.

However, a selection effect in favor of the discovery of brighter NEAs in a magnitude limited survey may explain such trend. A simulation of the NEA discovery process and the possible selection effect involved in the choice of the objects to be observed in the thermal infrared is an important future work that can clarify this issue.

7.1.4 The ambiguous taxonomic classifications of six asteroids have been clarified in the light of the new albedo values.

The taxonomic classification of the NEAs 1997 XF_{11}, 4666 Nereus, 5751 Zao, 15817 Lucianotesi, 2000 BG_{19}, 2002 BM_{26} have been revised in the light of newly derived albedos.

7.1.5 The apparent color temperature of the observed NEAs is phase angle dependent

The NEATM best fit parameter η is inversely related to the apparent surface color temperature of asteroids (via Eq. 5-1).

The NEATM η-value is phase-angle dependent and, on average, significantly higher than the value 0.756 adopted by Lebofsky et al. (1986) in their version of the STM, which was used to derive IRAS albedos of main-belt asteroids. We have shown that this effect is due to the fact that NEAs have larger thermal inertias than big main belt asteroids.

The best linear fit to the observed distribution of NEAs η-values is: $\eta=(0.011\pm0.002)\alpha+(0.90\pm0.07)$, where α is the phase angle.

7.1.6 *The variation of the color temperature with phase angle depends on the albedo*

Darker objects have a steeper increment of η with the phase angle and smaller η-values at low phase angles. The higher color temperature displayed by these object at phase angle approaching zero is indicative of a thermal inertia lower than the mean value. Moreover, darker objects might have more pristine and rougher surfaces leading to a stronger beaming effect (and consequently to a lower η) than objects with higher albedos.

7.1.7 *The observed distribution of the color temperature with the phase angle can be explained in terms of thermal inertia and surface roughness*

We have developed a thermophysical model which takes into account the combined effects of surface roughness, thermal inertia and rotation rate on the thermal infrared emission of asteroids.

We show that the thermal properties of the large majority of the NEAs in our database can be described by means of that model.

7.1.8 *The best-fit thermal inertia of the observed NEAs is 550±100J m^{-2} $s^{-0.5}$ K^{-1} or about 11 times that of the Moon*

For random orientations of the asteroid spin vector with respect to the Sun and the observer, η-values are constrained by two curves in the η-α plane. Those curves are function of the thermal parameter Θ and the mean surface slope $\bar{\theta}$. We have corrected the observed η-values of NEAs to take account of their different rotation rates and we have looked for the set of curves giving the best fit to the observed η-values. Surface roughness is not well constrained, but we found that $20°\leq\bar{\theta}\leq35°$ is in good agreement with the observations.

Our result put constraints on the strength of the Yarkovsky effect on kilometer and sub-kilometer size bodies. As an example, we have calculated the semimajor axis drift rate for an object with NEA-like thermal inertia, with a diameter of 200 m, a rotational period of 5 hours at 2 AU from the Sun. We derive a value of 9×10^{-4} AU/Myr.

Our best estimate of the thermal inertia of the observed NEAs indicates that these bodies have surfaces with a regolith courser than the lunar one and, very likely, their surfaces differ in fractional rock coverage from those of large main belt asteroids.

However, note that our thermophysical model used is still idealized. (spherical shape, roughness described by simple hemispherical craters, lack of realistic surface topography)

7.1.9 There are asteroids with anomalously low color temperature

However, our thermophysical model cannot explain the very low color temperature observed for NEAs 3671, 2002 BM_{26} and 1999 NC_{43}. Perhaps more sophisticated thermal models including the effect of positive and negative relief and the effect of lateral heat conduction may be necessary in those cases.

Moreover, our idealized thermophysical model assumes the emissivity equal to one at every wavelength. However, if this is not the case variations of the apparent color temperatures of asteroids may result.

7.1.10 The observed distribution of color temperature allows a calibration of thermal models for applications to NEAs

A refinement of the default η-value for the NEATM is proposed by using the linear relation in Eq. (5-2), when it is not possible to derive η via a fit of the thermal infrared continuum.

The STM with a fixed η-value equal to 0.9 and an infrared phase coefficient β_E=0.015 mag/deg (instead of η=0.756 and β_E=0.01 mag/deg) derives diameters in better agreement with radar results. Such modified STM is also in better agreement with thermophysical model simulation carried out with the average value of the thermal inertia and the mean surface slope that we have derived for NEAs.

The use of the modified STM or the NEATM with default η-value given by Eq. (5-2) provides the same results for phase angles up to 30-40°.

7.1.11 We have derived a quantitative assessment of the accuracy of thermal models and a correction function for the nominal results of the NEATM and the STM

We have numerically estimated a correction function for NEAs radiometric diameters and albedos derived by means of the STM and of the NEATM, provided that spin status and thermal parameter of the asteroid are known.

When such information is not available, the accuracy of NEATM results can be still estimated on the basis of the derived η-value.

In the case of NEATM, errors on the derived albedos are very rarely larger than ±20% for observations obtained to within ±40° of phase angle.

At large phase angle ($|\alpha|>40°$), the accuracy of the NEATM is worse and derived albedos are likely to be underestimated if η is larger than 1.5. This is consistent with the fact that this model ignores the emission from the night side of the asteroid.

7.2 Future works

7.2.1 Application of thermophysical models to NEAs

We have shown how the use of simple thermal models can provide valuable information on the sizes and albedos of NEAs. However, the use of more sophisticated thermophysical models has to be considered if one wants to get insights into thermal and surface properties of single asteroids.

We have used our thermophysical model to get constraints on the average thermal inertia of NEAs. We have done that by fitting the distribution of the surface color temperature of a number of objects studied together. However, as in the case of 433 Eros and 5381 Sekmeth, we have shown that thermophysical modeling is very promising to study the characteristics of single objects. And indeed, NEAs appear the most intriguing and suitable bodies of the solar system where performing such study. They often appear under a large range of illumination and observing geometries and have a large variety of surface characteristics. A very interesting project would be to include radar and/or photometrically derived asteroid shapes along with their spin vector status into the thermophysical model.

7.2.2 *Study of the contribution of a selection bias in the observed trend of increasing albedo with decreasing size*

Small objects appear, in general, to have albedos higher than the value implied by their taxonomic classification (according to taxonomic schemes based on the study of large main belt asteroids).

However, a selection effect in favor of the discovery of brighter NEAs in a magnitude limited survey may explain such trend. A simulation of the NEA discovery process and the possible selection effect involved in the choice of the objects to be observed in the thermal infrared is an important future work that can clarify this issue.

However, the present statistics is still poor and strongly affected by possible observational and selection biases. A simulation of the NEA discovery process and the possible selection effect involved in the choice of the objects to be observed in the thermal infrared is an important future work that can clarify this issue.

7.2.3 *Study the range of thermal and surface properties of NEAs by means of thermal infrared*

Studying the range of thermal properties and surface structure present in the NEA population is possible by investigating the variation of the apparent color temperature, T_C, with the phase angle for selected near-Earth asteroids of different sizes and classes. Different effects such as thermal inertia and the infrared "beaming" due to surface roughness lead to different dependencies of T_C on phase angle. Measurements of T_C over a range of phase angle can therefore provide information on the physical properties of NEAs not obtainable by other means.

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