Impact Cratering - A Chaotic Process

Impact cratering is a fundamental solar system process that has occurred on all the planetary bodies and at all spatial scales ranging from micron size impact to basins that are hundreds of kilometers across. It is an unparalleled geologic process involving impact velocities of tens of kilometers per second and with the capacity to dramatically alter the geological landscape over several kilometers in a matter of minutes to hours, even for a small scale impact event. Lonar crater in Maharashtra with a diameter of about 1.8 kilometer provides an excellent example to illustrate the magnitude of change in an impact event as well as the scale to which it permeates (Figure 1). The impact process involves compression, displacement, excavation and melting of massive volumes of target material producing an altogether chaotic landscape. Rocks originally located at depth lie exposed at the surface along with the local lithology, minerals are shattered, melted and fused to various degrees, pulverized material is lofted as ejecta and emplaced up to several crater radii, melt material occurs in diversity of forms including small melt droplets, melt ponds, flows and in case of larger craters, huge melt sheets on the crater floor, usually embedded with un-melted rocks or clasts.

The picture painted here represents the intrinsic character of a cratering event. Needless to say, there will be differences amongst events, craters of different sizes and on different planetary bodies due to dependence on variety of parameters. All planetary bodies including our own Earth were battered with impact events in the past to the extent that craters formed the single, most abundant geological feature on planetary bodies. Earth’s Moon (Figure 2) provides the closest example of what our Earth and other planetary bodies must have looked like during the peak of impact events. Plate tectonics and other dynamic processes on Earth have erased most of the impact signatures on its surface today but the lunar landscape has largely remained the same over the past 3.2 billion years. Moon, therefore is an excellent place to study the products of impact cratering including impact melt deposits.

Lunar Impact Melt Deposits

Impact melt is a very broad term that is used in many different ways. In the context of remote sensing, impact melt can be defined as partially or completely molten material produced during the cratering process which cools off to attain varying degrees of crystallinity and diversity of morphologic forms. Impact melt deposits occur within the crater as well as outside with the proportion being influenced at least in part by the size of the crater. Larger craters tend to retain larger volume of impact melt on their floors [e.g. Grieve and Cintala, 1998].

Figure 1: Chaotic landscape around an impact crater illustrated at Lonar crater, Maharashtra. (a) Poorly sorted rocks forming a monomict (rocks of one dominant type) breccia unit illustrates the sudden excavation and freezing of a large rock fragment in random orientation along with material of significantly different size (rock hammer for scale). (b) Random mixture of melted and un-melted material exists at the smallest scale. The circled regions contain small fragments of glass (coin for scale).

Impact melt deposits on the Moon have provided some of the fundamental information about our solar system. Perhaps the most important insight has been the occurrence of late heavy bombardment or LHB, a period during which there was a very high rate of meteorite impacts on the Moon [e.g. Tera et al., 1974]. Later, it was found that LHB event happened across the solar system. This key finding was based on radiometric age dating of impact melt samples brought back by the Apollo missions which showed a clustering of ages around 3.8 billion years. There has been some recent modifications pertaining to the nature of LHB [e.g. Morbidelli et al., 2012] but the essential component of an intense bombardment episode still holds.
Earlier Studies:
Impact melt samples from returned lunar missions, meteorites and samples from terrestrial impact craters [e.g. Dence, 1971, Tompkins and Pieters, 2010] have been extensively studied in the laboratory providing crucial insights about their character including mineralogical and textural complexity (due to varied melt-clast proportions), wide range in crystallinity (glassy to completely crystalline) and provenance (source region). In the context of remote sensing, majority of the studies till recently have been focused on the morphological character of impact melt deposits. Some of the important insights that were obtained from these studies include the wide diversity of morphological forms of impact melt [e.g. Howard and Wilshire, 1975] and the strong influence of crater rim topography on the spatial distribution of impact melt around craters [e.g. Hawke and Head, 1977]. A limited number of remote sensing studies were also carried out from a compositional perspective [e.g. Smrekar and Pieters, 1985; Heather and Dunkin, 2003] but they had a relatively limited scope.

Another aspect of impact melt deposits which has been studied is their age with respect to the crater age. Image based age dating of pools of impact melt around large impact craters is carried out by counting craters on the melt surface and their comparison with standardized crater production function. In this context, a discrepancy was noted between crater ejecta age and age of the impact melt deposits despite the fact that both should have formed at the same time [e.g. Strom et al., 1968]. Similar differences have been observed with the more recent datasets and this problem is still unresolved although some aspects are a little better understood now than before [e.g. van der Bogart et al., 2010].

Recent Studies:
Lunar science is currently witnessing a renaissance aided
by the availability of high spatial and spectral resolution datasets in the visible, near-infrared, thermal and radar wavelengths from recent lunar missions from Japan (Kaguya), China (Chang’e-1, Chang’e-2), India (Chandrayaan-1) and the US (Lunar Reconnaissance Orbiter or LRO and Gravity Recovery and Interior Laboratory or GRAIL). The pre-existing knowledge about the Moon is constantly being revised and several new dimensions are being added. In this context, the understanding of impact melt deposits is also undergoing a significant enhancement. In contrast to the conventional utilization of visible wavelength imagery for the study of impact melt deposits, they are now also being analyzed using other datasets:

a) Textural Studies Using Radar and Vis-NIR Datasets
Impact melt deposits, specifically the impact melt flows, have been recently studied using radar datasets [e.g. Neish et al., 2014]. Compared to the visible wavelengths which interact with the very topmost layer of lunar surface (few microns), radar wavelengths are able to probe a little deeper and are sensitive to relatively larger rock fragments. As a consequence, several previously unknown impact melt flows have now been detected on the Moon based on radar data analysis (Figure 3). In addition, the spatial extent of previously known flows are much better defined. These studies have also highlighted the fact that smooth looking impact melt flows observed in visible imagery may have coarse grained clasts embedded in them which are easily detectable in radar data.

At grain sizes smaller than radar wavelengths, visible and near infrared datasets have been found to be useful to determine grain properties including their size distribution, shape and internal structure, which altogether influence their scattering properties. Some recent studies [e.g. Shkuratov et al., 2012; Wohler et al., 2014] have utilized these datasets obtained at different viewing geometries and have reported differences in the scattering properties of impact melt flows which could be linked to variety of factors including surface roughness, grain size and relative proportions of glass to crystalline minerals.

b) Mineralogical Studies Using Vis-NIR datasets: Remote mineralogical assessment of impact melt deposits did not receive much attention in the past. This is in contrast to their widespread occurrence at impact craters and basins.

Figure 4: (a) Color composite generated using visible and near infrared data reveals the presence of a mineralogically distinct sinuous impact melt feature (blue coloration outlined in white) at Copernicus crater. (b) Color composite draped over the topography data. (c) Visible imagery does not capture the sinuous feature. (d)-(f) The expression of sinuous feature in various spectral parameter images. All of them capture strength of mineral absorption bands at different wavelengths (IBD1000: band strength around 1000 nm, BD 1900: band strength at short wavelength region of 2000 nm, IBD 2000 nm: band strength across the entire 2000 nm band) (Taken from Dhingra et al., 2013, Published by Wiley & Sons)
High spectral and spatial resolution datasets are now being used to fill this big gap in our understanding. As with radar studies, the definition of impact melt deposits as something solely characterized by surface morphology, is also being refined by compositional studies. The recent discovery of a mineralogically distinct, >30 km long sinuous impact melt feature at Copernicus crater [Dhingra et al., 2013] illustrates this point best (Figure 4). The sinuous melt feature is only detectable compositionally and does not have any surface morphology including topographical variations, making it largely invisible in optical imagery. In addition, the feature is also not detectable in radar datasets. Mineralogically, the sinuous melt feature is characterized by a low calcium-pyroxene while the nearby melt is rich in high calcium-pyroxene. All these characteristics make the sinuous melt feature a unique addition to our knowledge of impact melt deposits. At the same time, the systematic differences in mineralogy of the sinuous melt feature with respect to the nearby impact melt represents a surprising orderliness in the chaotic geologic setting of an impact crater.

Apart from mere identification of mineralogical differences, the compositional character and contrast also provides an opportunity to interpret the geological history of the region, at times leading to better understanding of the evolutionary processes at work. In the case of sinuous melt feature at Copernicus crater, its distinctly different mineralogy from the impact melt in the vicinity that was produced in the same impact event, has been interpreted as the result of an inefficient mixing of impact melt, a previously unknown fact in the context of the Moon.

New Insights from High Resolution Visible Imagery:

The conventional method of using optical imagery for studying impact melt deposits is still a powerful method and provides the observations at the highest possible resolution compared to other datasets. The super high resolution optical imagery (< 1 m to 10 m) available from the current and recent missions is very well suited to study the level of complexity (and chaos) that is associated with impact melt deposits. Recent studies in this regard have revealed significantly more details including the ability to identify multiple generations of flows within a large melt flow, identification of impact melt at small-sized craters, complex fracturing patterns in impact melt, evidence for subsurface flow and relatively longer cooling history than previously thought [e.g. Bray et al., 2010; Plescia et al., 2012, Stopar et al., 2014].

The current availability of different types of datasets is enabling their synergistic use and thereby maximizing the scientific returns. The study of impact melt deposits has immensely benefited with the use of multiple datasets [e.g. Dhingra et al., 2013, Srivastava et al., 2013; Neish et al., 2014] and has also highlighted ambiguities pertaining to their identification and characterization [e.g. Chauhan et al., 2012; Srivastava et al., 2013, Plescia and Spudis, 2014]. In addition to observation based interpretations, the high resolution datasets are also providing crucial information for modeling the physical properties and thermal evolution of impact melt deposits [e.g. Denevi et al., 2012; Xiao et al., 2014].
The fact that life exists on Earth is no secret. However, understanding the origin of life, its evolution, and the future of life on Earth remain interesting issues to be addressed. That the regions between stars contain by far the largest reservoir of chemically-bonded matter in nature obviously demonstrates the importance of chemistry in the interstellar space. The unique detection of over 200 different interstellar molecules largely via their rotational spectra has laid to rest the popular perception that the vastness of space is an empty vacuum dotted with stars, planets, black holes, and other celestial formations. Astrochemistry comprises observations, theory and experiments aimed at understanding the formation of molecules and matter in the Universe i.e. the formation of Universe. Molecules with a well-understood chemistry in the interstellar medium can be used as probes of astrophysical phenomena. Astrophysics covers a wide range of issues ranging from the study of our solar system to the study of the interstellar medium (ISM). The interstellar molecules serve as the most powerful tool for probing deep into the interior of molecular clouds. Interstellar clouds are significant because it is from them that new stars, and consequently new planets, are formed. Understanding how the simple molecules present on the early earth may have given rise to the complex systems and processes of the present-day biology is widely regarded as one of the chemistry’s great unsolved questions. The biologically important molecules so far detected in the ISM serve as significant tools towards addressing the chemical origin of life.

The ISM is simply all the stuff between stars. It is the matter that exists in the space between the stars. This matter includes gas in ionic, atomic and molecular form, dust and cosmic rays. It fills the interstellar space and blends smoothly into the surrounding intergalactic space. The ISM is composed of 99% gas and 1% dust. Of the gas in the ISM, 89% of atoms are H and 9% are He, with 2% of atoms being elements heavier than H and He, which are called ‘metals’ in astronomical parlance. Dust consists preferentially of particles of heavy elements. The ISM plays a crucial role in astrophysics precisely because of its intermediate role between stellar and galactic scales. It is important observationally, as it enables us, for example to observe the dynamics of the gas, such as rotation curves, because spectroscopic emission lines from the gas are prominent.

The basic approach in probing molecules in the ISM is to use spectroscopy to create a database of “fingerprints” from known molecules in the laboratory and then compare the stored readings to those captured with a spectrometer.