SAND2006-5682C

Impact Flash Spectroscopy at Impact Velocities Approaching 20 km/s

W.D. Reinhart, L.C. Chhabildas, T.F. Thornhill, J.L. Brown R. J. Lawrence

1. Introduction

Impact-flash phenomenology has been known for decades, and is now being considered for applications where remote diagnostics are required to observe and diagnose impacts on satellites and space craft where micrometeoroid and orbital debris impacts are common. To technically establish this capability in the laboratory, we have conducted a series of experiments at impact velocities ranging from 6 to 19 km/s which is commensurate with impact conditions.. Two- and three-stage light-gas guns were used for the achievement of these velocities. Spectrally and temporally-resolved flash output addressed data reproducibility, and material identification. Usable data were obtained at visible and near infrared wavelengths. Standard atomic spectral databases were used to identify strong lines from all principal materials used in the study. The data were unique to the individual materials over the wide range of velocities and conditions examined. The time-varying nature of the signals offered the potential for correlation of the measurements with various aspects of the target configuration. We demonstrated that the impact flash spectra were qualitatively reproducible from shot to shot, and have confirmed the feasibility and credibility of using impact-flash spectroscopy for many space-related remote-sensing applications.

2. Background

The phenomenon of impact flash has been known for many years, even at the relatively modest engagement velocities of several kilometers per second. The relevant processes were analyzed in some detail [1, 2, 3] as long ago as the late sixties and early seventies. More recently impact flash has been proposed as a technique for remote diagnostics associated with the analysis of impact events such as meteoroid impacts on space-based assets [4].

2.1 Capabilities and Program Description

We have recently revisited this impact-flash phenomenology by bringing into play our new capabilities for generating hypervelocity impacts at velocities greater than 19 kilometers per second. This particular effort has looked at the flash from impacts over a range of velocities from 6 to 19 km/s. Our general goals were to use the measurements of the time- and spectrally-resolved flash output to address: 1) data reproducibility; 2) material identification. Flyer and target materials involved various combinations of aluminum, iron, indium, and titanium. In this study we have made measurements both in the visible and near infrared (NIR) spanning the wavelengths fro 350 to 1800-nm. For these experiments optical multi-channel analyzers (OMA) were used and they gave reading times of almost one millisecond, consisting of up to 200 individual data traces, 5 μs resolution in the visible. The OMA looking within the NIR provided millisecond recording and 20 μs resolution. The OMA's resolution refers to integrating over the mentioned time then digitally shifting into memory.

Using standard tabulations of atomic spectral data [5] we were able to identify strong spectral lines from all the principle materials used in the various shots. Using these results we demonstrated that the impact flash spectra were qualitatively reproducible from shot to shot with the same experimental techniques, as well as relocating the sensor with respect to impact. Further, the signals were unique to the individual materials over the wide range of velocities examined, even though some velocity dependence was observed.

One of the major problems for remote diagnostics is that the closing velocities for these engagements will always be high—typically above the sound speeds of the materials involved—and as such they are considered hypervelocities. Because hypervelocity impacts always produce an *impact flash*, it is a reasonable assumption that this radiative signal contains information on the materials and time sequence involved in the interaction.

3. Experimental Effort

We will utilize the two-stage light gas gun to obtain desired impact velocities and/or stress states. The gun will be shot in the standard two-stage ballistic configuration with either a sphere launch or flyer plate facing on a lexan sabot, the three-stage high velocity plate launch arrangement and the Enhanced Hypervelocity Launcher (EHVL) design utilizing the Impact Generated Acceleration Reservoir (IGAR). These varied launch techniques allow us to obtain impact velocities in the range of 6 to > 19 km/s.

3.1 Two - Stage Sphere Launch

The configuration and results shown in Figure 1 provided impact of aluminum spheres on aluminum targets at ~5.8 km/s, with the visible spectrometer viewing the debris generated after the target was penetrated (using fiber located ~ 0.3m directly behind the target). The three records (obtained from 3 separate experiments), cover the visible spectrum, from λ = 350 nm to λ = 800 nm. Most of the lines can be identified with aluminum, in the neutral sate Al (I), singly ionized Al (II), or doubly ionized Al (III). Even the Na (I) line at λ = 589 nm is prominent.

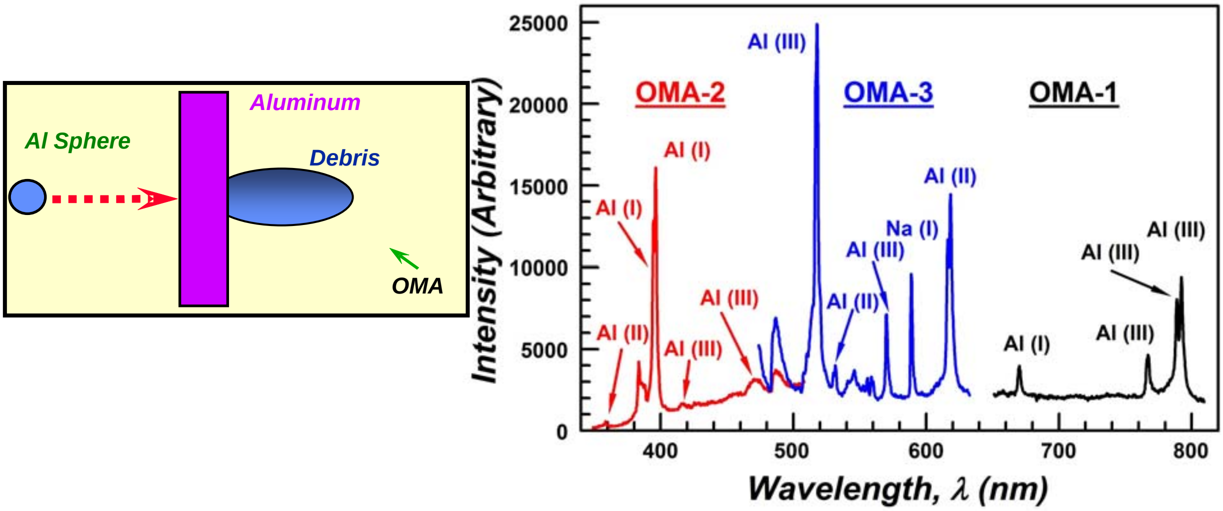

Fig. 1. Visible spectra from first experiments on Aluminum at approximately 6 km/s. In all experiments, the collection fiber(s) (used for collection of light and sent to the OMA) is located directly behind the target.

The sphere-launch technique was used to gain experience with our diagnostics, and perform controlled, high precision and relatively inexpensive experiments. These experiments, though not at the impact velocities generally associated with impact engagements, provided insight that distinct emission lines from various materials can be identified.

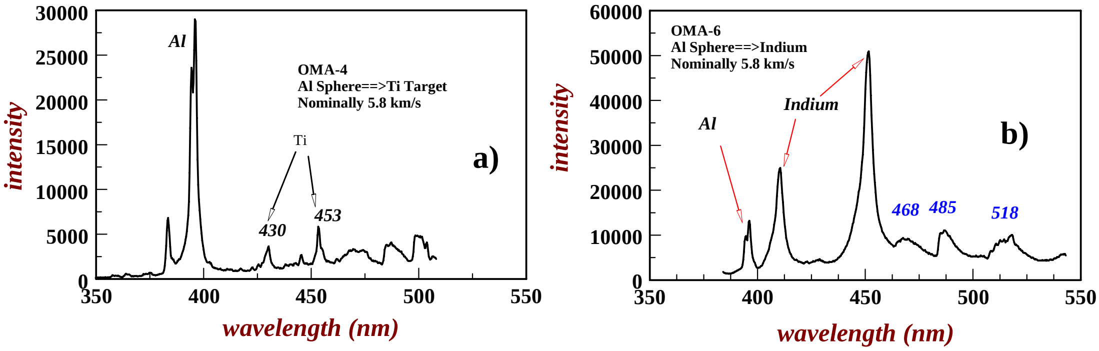

Fig. 2. Aluminum-sphere impacting titanium and indium provide unique, repeatable spectra at impact velocities of 5.8 km/s.

However, to prove proof-of-concept on impact flash and material identification, numerous experiments were performed with different target materials. Using the same impactor (aluminum) at the same engagement velocities, a data base is generated that describes material light signatures under hypervelocity impacts. Figure 2a and b show light spectra from an aluminum sphere impacting titanium and indium respectively. In both figures, very strong aluminum lines are prominent and at a very high relative intensity. Both titanium and indium produce reproducible spectra for every experiment that was performed with either material. Titanium was chosen as a material to identify, as it is the flier material of choice for Sandia National Laboratories three stage gun. Indium was chosen because of its low ionization potential and would have a high probability to provide a spectral signature for each experiment that it was used within. These experiments show very distinct emission lines, but minimal blackbody radiative characterisics.

Up to this point we have been using our small two stage light gas gun ballistic capabilities. The pressure states for all the experiments were approximately 85 GPa. These tests were conducted to better our understanding on how the diagnostics (spectrometers/OMA) perform while recording high-velocity dynamic experiments, while providing material spectral signature under well controlled high velocity impacts.

3.2 Flier Plate Configuration

The next phase of our study involved higher velocities and more complex target geometries. When there are impacts on satellites, or spacecraft, materials within the "target" are generally in intimate contact with each other. These experiments were performed at nominally 7 km/s with either a titanium or tantalum impactor. Tantalum was chosen for 1) provides the highest impact pressure upon impact to approach the states that are achieved at engagement velocities on the two-stage light gas gun, 2) tantalum is a refractory material that does not exhibit "light" spectra in the visible or NIR (at these pressures). Titanium was used for obvious reasons in that it is a material we have spectra for, and we will obtain higher stress states than that of aluminum.

In the configurations shown in Figure 3, a series of experiments were performed to determine if the diagnostics could identify materials in simple to complex target geometries at higher pressure states.

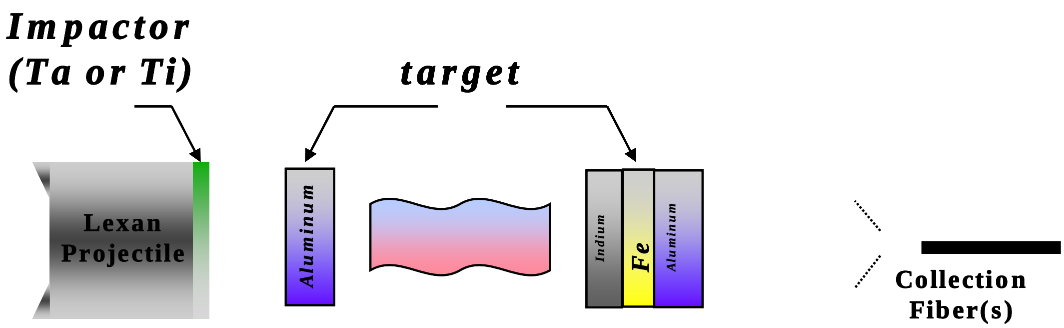

Fig. 3. Flyer plate configuration. Sabot faced with a high impedance material (such as tantalum) or a single titanium flyer plate is launched at 7 km/s. Targets can vary in complexity from a simple single target configuration to multi-layer setup. The collection fiber is simply a 900 um open ended/cleaved fiber with a direct connection to the spectrometers and views the aft surface of the impact event.

3.2.1 Simple Test:

In the simple test we are nearly duplicating the configuration of the experiment described in figure 1. The similarities are that the materials will be the same – aluminum and titanium. Herein lies the primary difference; the impactor is titanium and the target is only aluminum and the velocity is increased providing an increase in impact pressure to nearly 120 GPa. What is expected is that we should see higher intensity spectra of both titanium and aluminum. Figure 4's spectra of titanium impacting aluminum at 7 km/s, does indeed provide significant increase of light intensity signatures of both titanium and aluminum, however, the intense aluminum lines shown in figure 2 are not prominent. Intensity of the primary titanium lines did indeed increase. It is not entirely clear why the reduction of intensity of the aluminum lines, but it is known that we should see an abundance of those aluminum lines for this test.

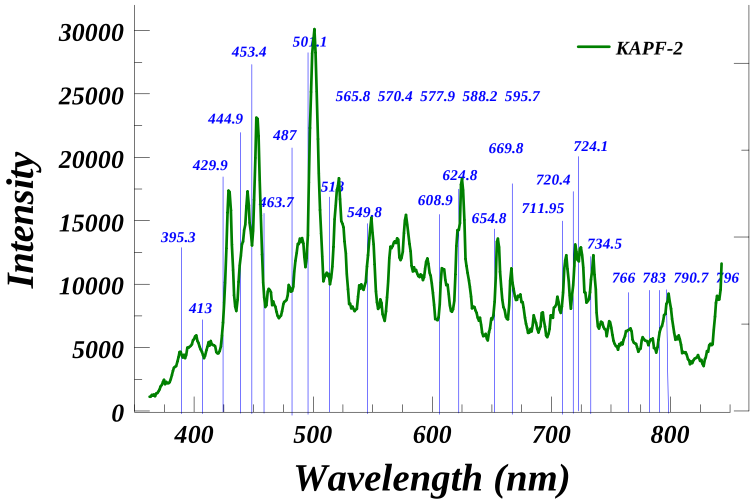

Fig. 4. Simple Test: Our basic lines of Ti and Al are present; however there appears to be more lines coming into view as the pressure states are increased. This could be related to the different ionization states the materials are going through.

These emissions show characteristics of both blackbody radiation and line emission. On the first experiments with a sphere, the blackbody characteristic is not as pronounced. One can speculate that the increased blackbody appearance is due to increasing pressure or the radiative properties of the shocked materials.

3.2.2 Complex Test: Multi-layered Target

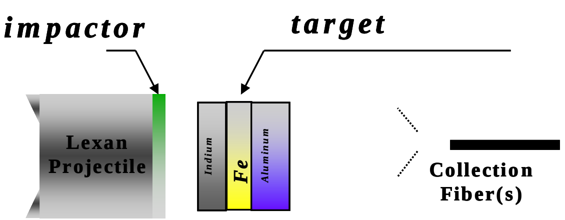

Fig. 5. Complex multi-layered target. Materials glued within Lexan mounting ring

For this experiment we have added an additional OMA which will observe the event in the NIR. This experiment should provide the most severe test of the diagnostics for material identification. For this configuration, we will be impacting the multi-layered target (with the impact directly on Indium) with tantalum. This in itself increases the impact pressure by nearly 3 times the previous configuration-300 GPa. The fibers used for collection of the light are still located behind the target, but the target-fiber separation was increased to over a meter. The fiber was pushed back for the NIR OMA so additional read time could be recorded. As we mentioned earlier, the resolution of the system is integrated over 20 µs but the shifting of the data into memory takes another 55 µs. The 75 µs required to obtain a single trace mandates the separation—because debris clouds from impact can be greater than 10 km/s. This experimental configuration (shown in figure 5) shows feasibility for allowing the identification of materials within a fragmented debris field. Again, we see the typical emission lines as well as a large blackbody radiative characteristic from this experiment.

Figure 6 shows that materials can be identified during this impact experiment. The probes are located so that the first material observed is the aluminum. All the materials within the target are identifiable over the time of the event (nearly 300 µs) in both spectrometers.

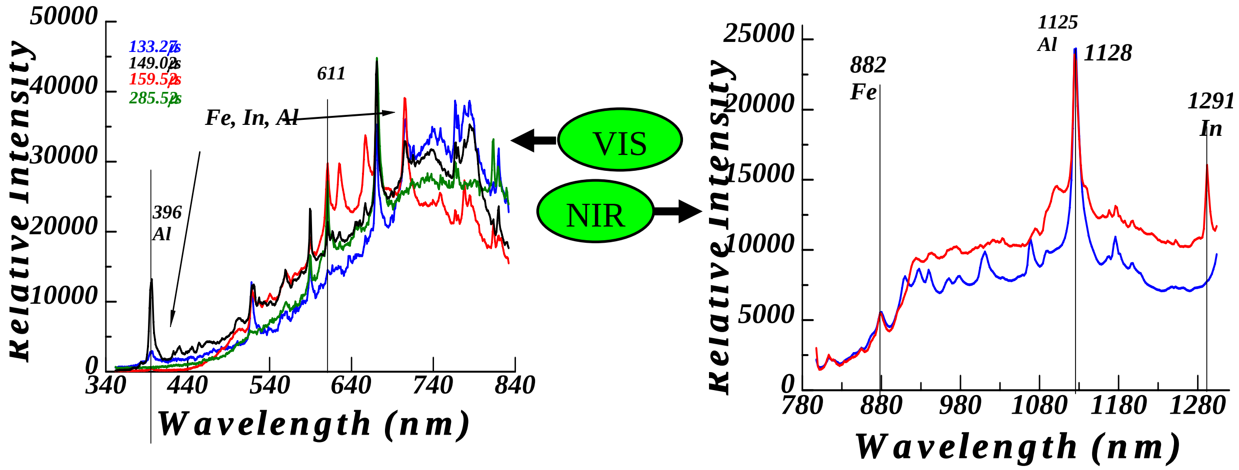

Fig. 6. Materials can be identified in a complex target and looking through the fragmented debris field.

3.3 Three-Stage Flier Plate Configuration

The next step in this study is to increase velocity of the flyer and the fragments, and perform a systematic study to investigate how velocity will or will not change the signatures of the data. Using a basic target configuration (figure 1) we launched a Titanium flyer plate at ~ 11km/s into an aluminum target. Though the impact pressures (250 GPa) were lower than the previous configuration (Ta impacting In), the advantage of launching a single plate provides a cleaner experiment. By cleaner, we mean that we eliminate the lexan sabot and will impact with a material that we have spectrally characterized and will not have to contend with how the additional material affects the experiment.

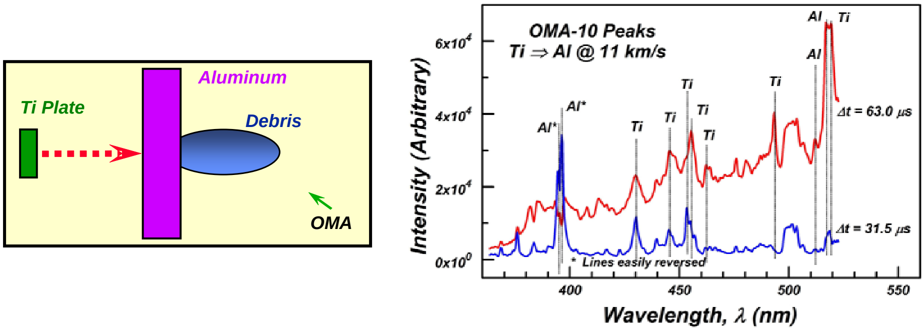

Fig. 7. The spectra from the experiment at 11 km/s, confirms that the lines for the experimental materials are identifiable.

Figure 7 describes the impact technique and the spectra obtained from the experiment. The light signatures show that materials can be identified and are still visible many microseconds after the initial impact. What is interesting to note, is why we do not see multiple lines of aluminum as we have seen in previous experiments? This could be an effect of the ever increasing blackbody radiative characteristics of the experiment. The back-body radiation characteristic has become more evident as the impact velocities and pressures states have been increasing.

3.4 Enhanced Hyper-velocity Impact

Finally, we took the flash diagnostics to our highest velocity -- over 18 km/s. However, the fliers are now small particles. What we found that even though the geometry is different, the light spectra still allows easy identification of materials involved in the impact event. In fact the intensity seems to have increased in some cases.

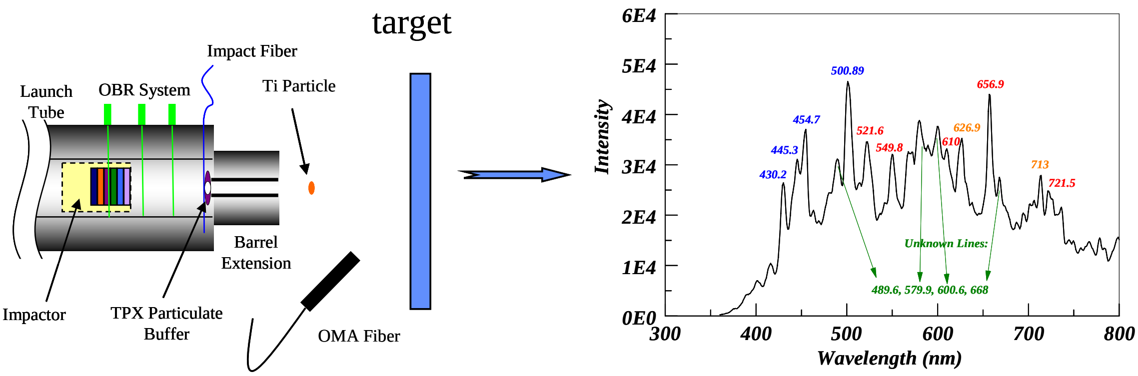

Fig. 8. Titanium particle launched at 18.4 km/s into an aluminum target. Spectra observed at ~ 3 us after impact.

Figure 8 describes the experimental setup for the Enhanced Hypervelocity Launch configuration where a titanium particle (1mm thick x 3mm diameter) was launched at 18.4 km/s. The spectrometer identified the materials within the target as well as still identifying the titanium particle. Our predominant lines of aluminum that have been evident at the lower velocities have all but disappeared—being ingulfed in the increasing intensity of the blackbody.

4. Summary

In this study we have collected time-resolved optical signatures from a number of tests that went from the very simple target complex target multi-layer configuration. We have provided a proof of concept that high-speed, high-resolution spectroscopy can identify materials that are involved in hypervelocity impacts. Though we are just in the early stages of developing this technique, one can see that the application of this is far reaching. These optical signatures or emissions are really an optical fingerprint of the materials upon impact.

Orbital debris is recognized as a serious and growing threat to space exploration for spacecraft and satellites. While basic there is some information on material composition, the measurements of orbital debris size and velocity distributions cannot distinguish material type. The understanding of impact flash signatures can lead to the ability to determine not only size and velocity, but material type.

If the ability to characterize target materials can be established, the next step would be to determine size, thickness of the targets to much more complex targets. Hydrocode simulations may then be used to provide more of a predictive capability for the state and temperature of a material that is jetted from the impact.

Reference

[1] Jean B, Rollins TL. Radiation from hypervelocity impact generated plasma. *AIAA Journal*, 1970; **8**: 1742-1748.

[2] Eichhorn G. Measurements of the light flash produced by high velocity particle impact. *Planet. Space Sci.*, 1975; **23**: 1519-1525.

[3] Eichhorn G. Analysis of the hypervelocity impact process from impact flash measurements. *Planet. Space Sci.*, 1976; **24**: 771-781.

[4] McDonnell JAM. HVI phenomena: applications to space missions. *Int. J. Impact Eng.*,1999; **23**: 597-619.

[5] Reader, J., and C. H. Corliss, Eds., “NIST Spectroscopic Properties of Atoms and Atomic Ions Database,” NIST Standard Reference Database 38, National Institute of Standards and Technology, Gaithersburg, MD, 1992.