The Zeeman Effect in a Radiating Magnetohydrodynamic Flow

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Introduction

Overview

- What is the Zeeman effect?
- Prior research
- Why are we studying it?
- Experimental observations
- Implications

The Zeeman effect

$$\Delta E_B = g_J \mu_B B M_J$$

Quantum mechanical interaction between orbiting electrons and external magnetic field

Coupling of spin and orbital angular momentum

Split spectral lines due to new energy levels

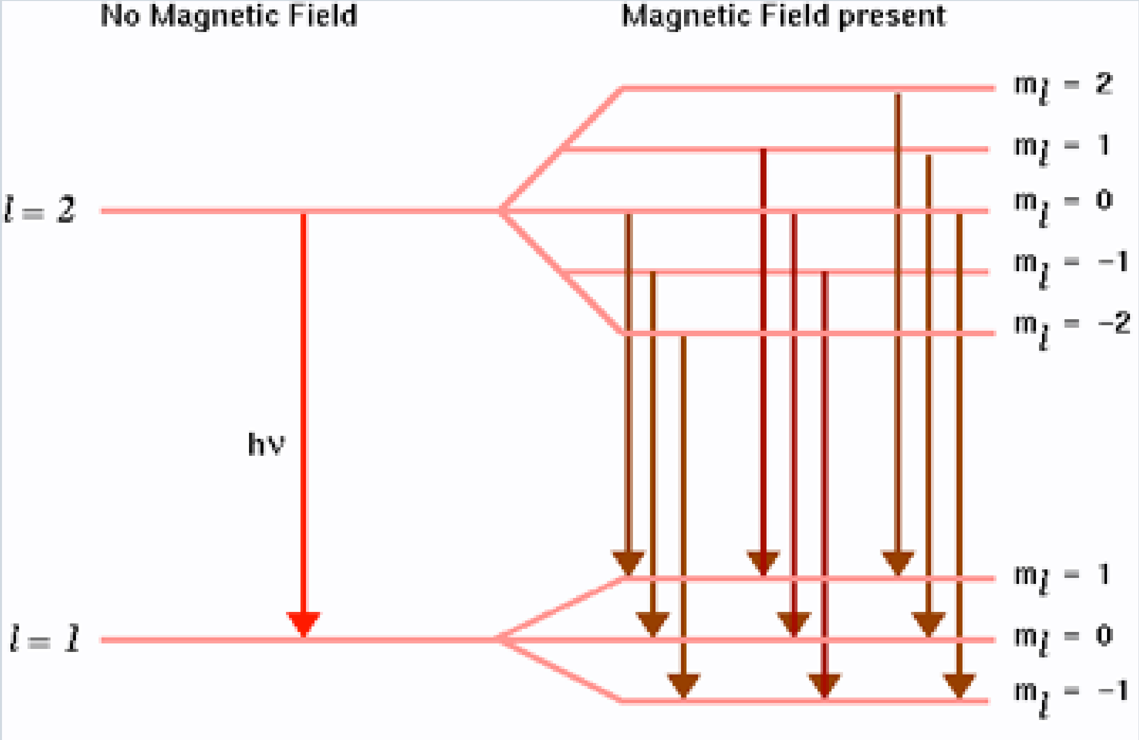
New lines dependent upon:

Lande' G factor (g)

External field strength (B)

Bohr Magnetron (μ_B)

Angular momentum quantum number (M_j)



Prior research

Prior research

Prior research has considered the Zeeman effect in absorption spectroscopy

- Takizawa et al (2006), Phys. Fluids **18**, 117105, https://doi.org/10.1063/1.2375076
- Matsuda et al (2008), Phys. Fluids **20**, 127103, https://doi.org/10.1063/1.3054149

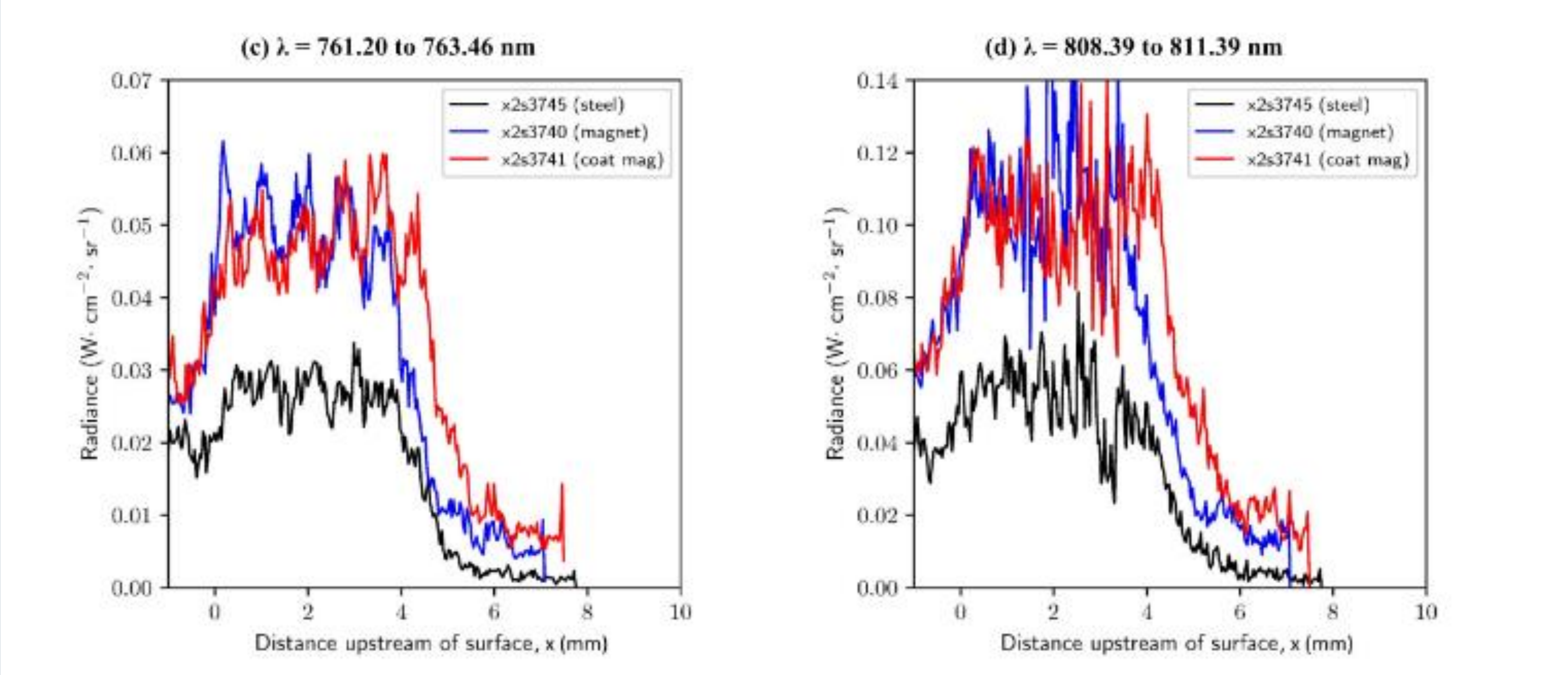
  - Arc-Jet experiments
  - Anomalous absorption coefficients in the presence of a magnetic field
  - Reduced absorption across a broader range of frequencies

  - The Zeeman effect does influence absorption in Magnetohydrodynamic flow

Prior research

The basis (and support) for this study:

- Gildfind et al (2018), AIAA Conference
- Expansion tunnel experiments
- 0.8T surface magnetic field strength, 1.5” diameter neodymium magnet
- 6 km/s Argon flow



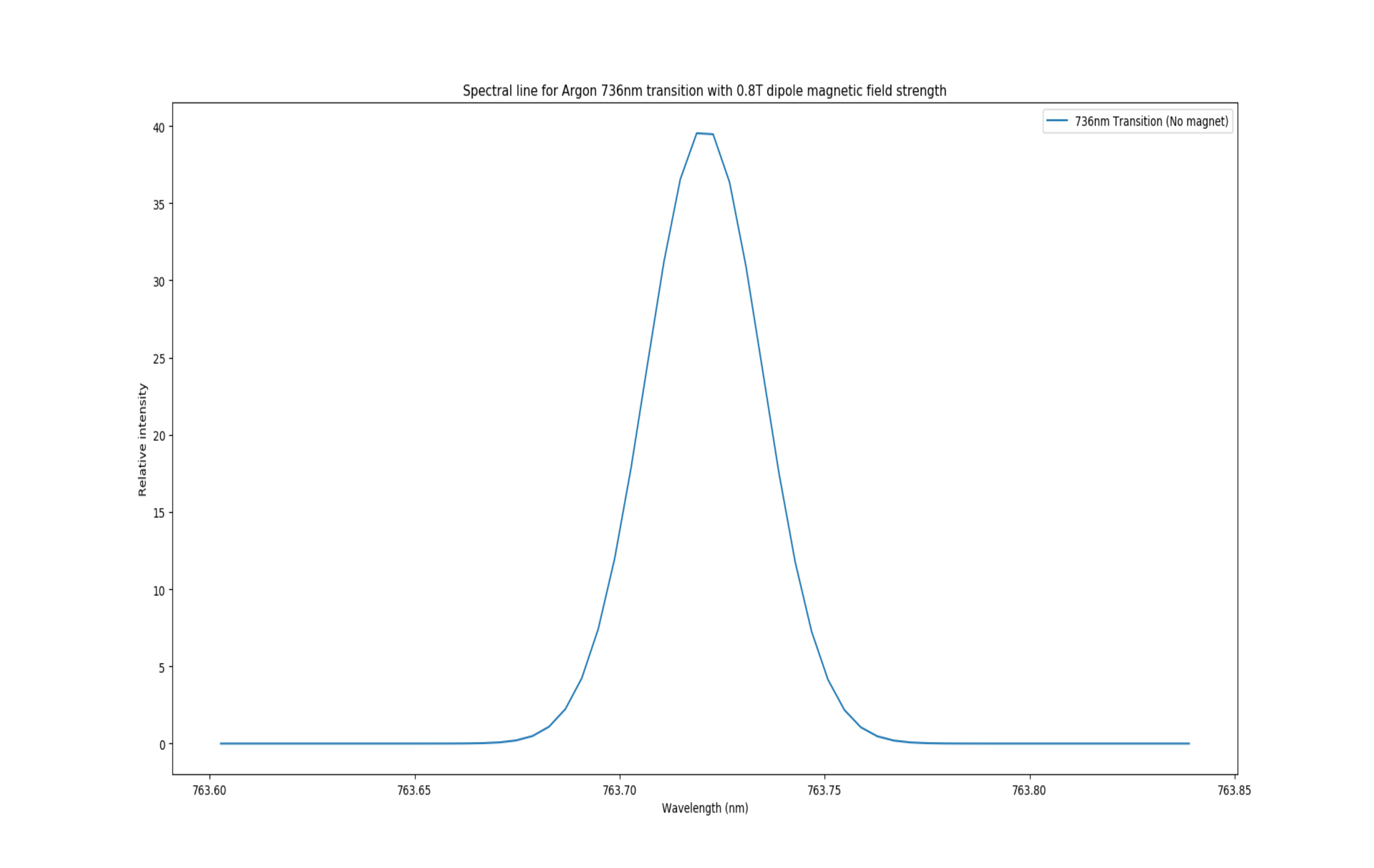
Theory

HOW DOES THE ZEEMAN EFFECT INFLUENCE RADIANCE?

Zeeman Effect in Argon Spectra

This study (and MHD study at UQ) has, thus far, been limited to argon flows

- Spectra of the 763nm line:
  - Field strength at surface – 0.80T
  - Angle of magnet – NS orientated with flow



Relative Intensity & Wavelengths

Relative intensity for Argon 763nm components: $(\Delta J = 0)$

- $\Delta m = 0$
  - $Z = M^2$
- $\Delta m = 1$
  - Z = $\frac{1}{4}((J - M)(J + 1 + M))$
- $\Delta m = -1$
  - $Z = \frac{1}{4}((J + M)(J + 1 - M))$

- Z = Relative strength
- J = Upper energy level degeneracy
- M = Upper energy level Spin angular momentum

- New energy levels can be found from:
  - $\Delta E_B = g_J \mu_B B M_J$
- 20+ New transitions in the presence of a magnetic field
  - Large matrices/ computationally expensive

Absorption

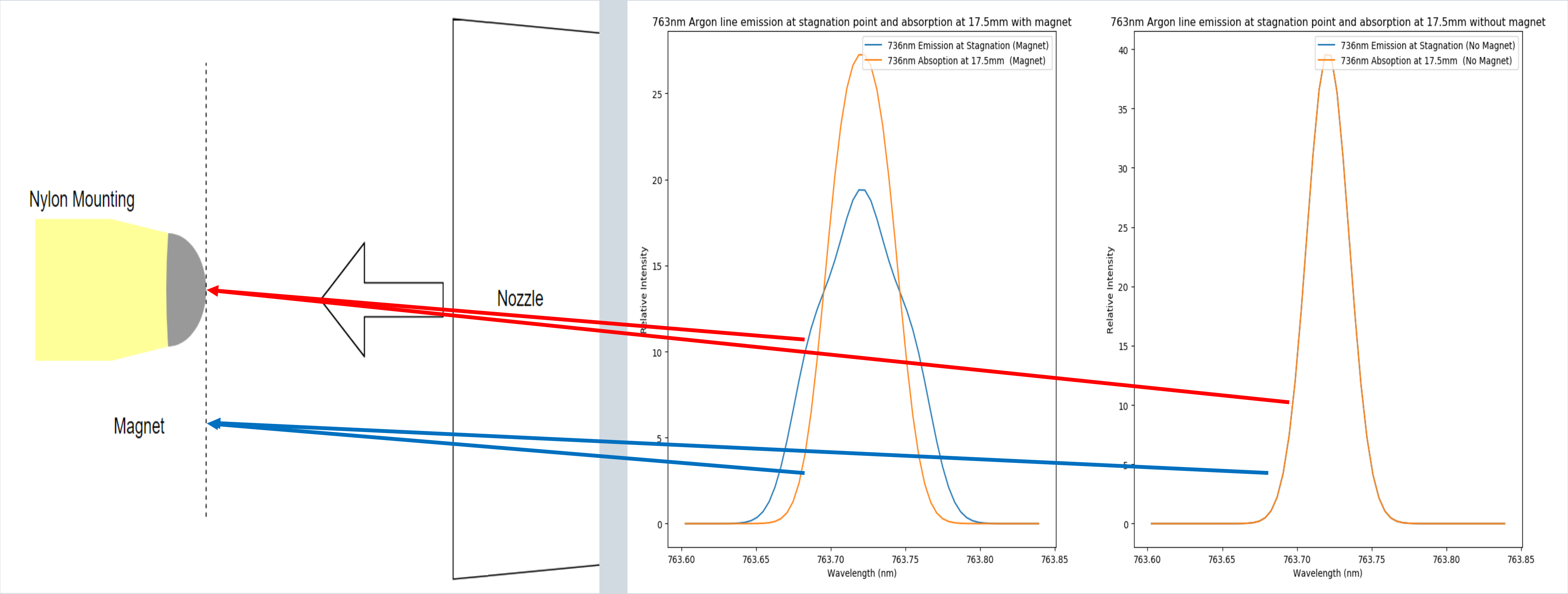
Absorption coefficient:

K = Relative strength of Zeeman component x Traditional Absorption coefficient x Line shape

- Varying Line shape varies significance of effect

$$K_{\lambda Z} = \frac{\lambda^4}{8\pi Q} \frac{Z(J, M, \Delta J, \Delta M)}{\sum_{m_i=-j}^{j} \sum_{\mathrm{m_f}=m_i-1}^{m_i+1} Z(J, M, \Delta J, \Delta M)} A_{if}\, g_i\, n_{total} \left(\exp\left(\frac{-E_i}{k_B T(x)} \right) - \exp\left(\frac{-E_f}{k_B T(x)} \right) \right) \sqrt{\frac{1}{2\pi w_{emit}}} \exp\left(-\frac{1}{2} \left(\frac{\lambda - \lambda_0}{w_{emit}} \right)^2 \right)$$

Holistic effect



Verification

LIMITATIONS OF THE MODEL

Limitations

Poorly defined Half-width and Density reduce validity

Implementation of flow coupled, 3D solver for multiple gasses necessary…

CFD dependency

Multiphysics problem, how much of observed phenomenon can be credited to Zeeman effect?

Results

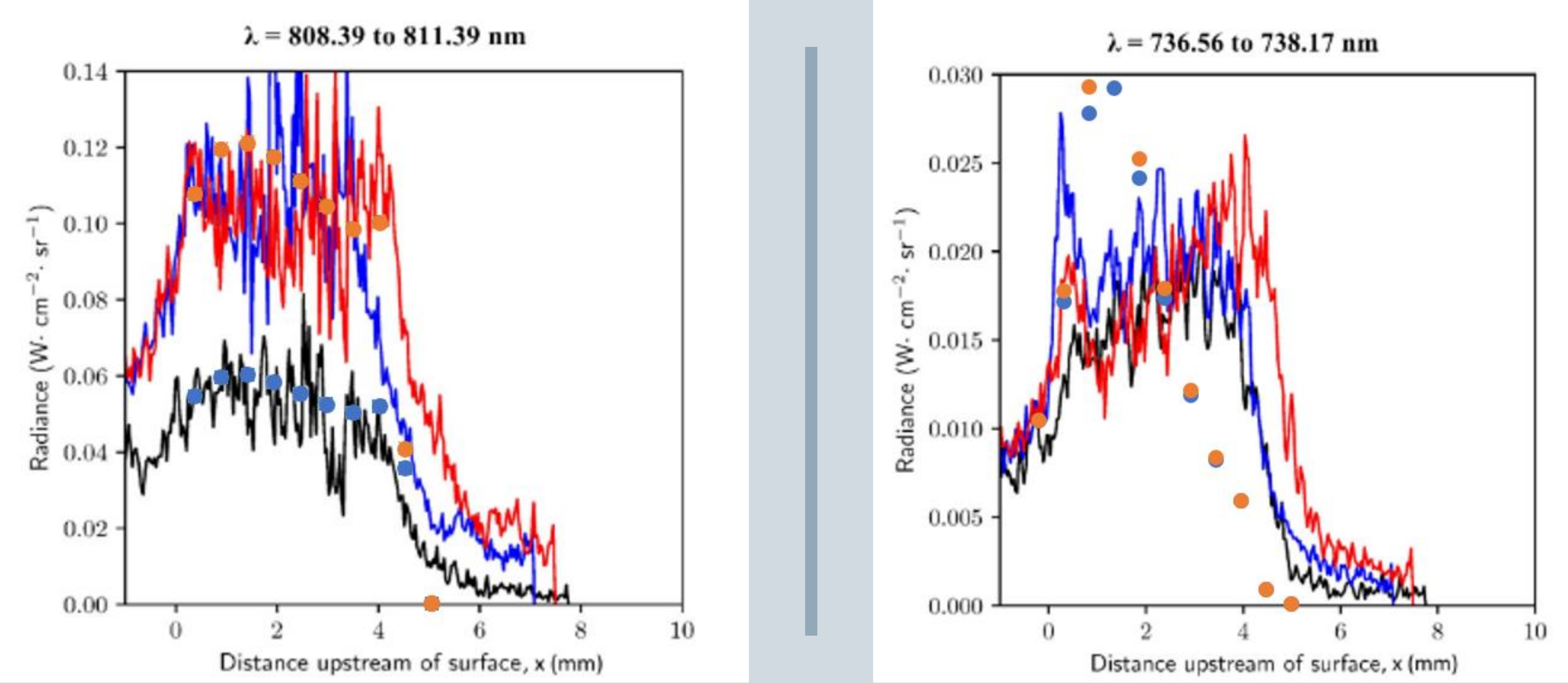


Figure 3: Spatial radiance from 0mm ahead of the body to 8mm ahead of the body over two wavelength ranges adapted from (Gildfind D.E. 2018). Red line: Coated magnet (X2S3741), blue line: Magnet (X2S3740), black line: Steel ball (X2S3745), orange points: Simulated radiance for a magnet including Zeeman effect, blue points: Simulated radiance for a steel ball including the Zeeman effect)

Applications

The impacts of the Zeeman effect on MHD research and flight testing are significant:

- Magnetic effects on flow present in radiative regime
- Flow diagnostics such as Stark broadening cannot neglect the Zeeman effect
- Additional radiation from shock layer cools flow
- MHD thermal protection systems cannot neglect Zeeman effect (increased radiation to the body)

Future Work

Future work will focus upon investigating the predictions of the mathematical model

- Direct observation of splitting
- Polarization effects
- Spatial dependency of absorption

As well as leveraging findings:

- Improved flow diagnostics
- Code development to support 3-D (or realistically hemispheres), broad spectrum, multi-gas simulation
- Accurate predictions of implications for spacecraft design and MHD aerobraking systems