Direct Measurements of Nonlocal Heat Flux by Thomson Scattering

Distance from target ($\mu$m)

$P_s$ (normalized units)

$q_{TS}$

$q_{SH} = -\kappa \nabla T_e$

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Nonlocal heat flux was measured using Thomson scattering from electron plasma waves

- Classical theory is in good agreement with the measurement at the lowest-gradient location
- The measurements show a reduction in heat flux from classical Spitzer–Härm theory in regions of large temperature gradients (\(\lambda_{ei}/|L_T| > 0.01\))
- The differences are consistent with nonlocal effects
- Simulations using the Schurtz–Nicolaï–Busquet (SNB) model calculate heat flux slightly reduced from classical values in the nonlocal region and overestimate the heat flux in low-gradient locations

Collaborators

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An accurate description of thermal transport in plasmas has large implications in direct-drive inertial confinement fusion.

Classical thermal transport (i.e., Spitzer–Härm) requires the collisional distance of electrons to be small compared to the temperature scale length. 

“Local” conditions:

\[ L_T = \frac{T_e}{|\nabla T_e|} \gg \lambda_{ei} \]

\[ q_{SH} = -\kappa \nabla T_e \]

Classical theory only requires information (including \( \nabla T_e \)) at a particular location to determine heat flux.
The classical model breaks down in regions with large temperature gradients.

The validity of the classical theory can be expressed in terms of the collision parameter $\lambda_{ei}/L_T$. 

**Local** conditions

$$L_T = \frac{T_e}{\nabla T_e} \gg \lambda_{ei}$$

**Nonlocal** conditions

$$L_T \approx \lambda_{ei}$$
The Spitzer–Härm (classical theory) model accounts for heat flux by introducing a correction term to the electron distribution function

\[ f_e^{\text{SH}}(v) = f_e^M(v) + \frac{\lambda_{\text{ei}}}{L_T} f_1(v) \]

**Projection of \( f_1(v) \) along \( \nabla T_e \)**

**Third velocity moment of \( f_1(v) \) projection**

\[
\int_{-\infty}^{\infty} f_1^{\text{SH}}(v_z) \, dv_z = 0
\]

Conserves number of particles

\[
q \propto \frac{\lambda_{\text{ei}}}{L_T} \int_{-\infty}^{\infty} v^3 f_1^{\text{SH}}(v_z) \, dv_z
\]

\[
= -\kappa \nabla T_e > 0
\]

Nonzero heat flux
The collective Thomson-scattering spectrum is sensitive to the electron distribution function

\[
\mathcal{P}_s \propto \frac{f_e(\omega/k)}{1 + \chi_e^2}
\]

\[
\chi_e \cong \int_{-\infty}^{\infty} \frac{k \cdot \partial f_e/\partial v}{\omega - k \cdot v} \left| v = \omega/k \right| dv
\]

\[
f_e^{\text{SH}}(v) = f_e^M(v) + \frac{\lambda_{ei}}{L_T} f_1(v)
\]

\[
v_\phi = \omega/k
\]

\[
q_{fs} = n_e T_e v_{te}
\]

A Milder et al., BO7.00015, this conference.
The collective Thomson-scattering spectrum is sensitive to the electron distribution function.

The effect of heat flux on electron velocity distribution.

\[ q_{\text{SH}} = -\kappa \nabla T_e \]

The amplitudes of the electron plasma wave features provide a measure of heat flux.

\[ v_\phi = \omega / k \]

\[ q_{\text{fs}} = n_e T_e v_{\text{te}} \]
Thomson scattering (TS) makes local measurements of plasma parameters (e.g., heat flux, electron temperature, and density)

\[ q_{SH} = -\kappa \nabla T_e \]

\[ \lambda_0 = 526 \text{ nm} \]

\[ m_0 = 526 \text{ nm} \]

\[ k \]

\[ \theta_s = 60^\circ \]

\[ \phi \]

\[ \lambda \]

\[ \text{Drive beams} \ (\lambda = 351 \text{ nm}) \]

\[ n_e \]

\[ T_e \]

\[ 1 - \cos \theta_s \]

\[ \lambda_0 \]

Experiments were set up to measure electron plasma waves parallel and antiparallel to the temperature gradient.
Thomson scattering makes local measurements of plasma parameters (e.g., heat flux, electron temperature, and density)

Experiments were set up to measure electron plasma waves parallel and antiparallel to the temperature gradient.
The Thomson-scattering spectrum provides an accurate measure of the electron temperature, density, and heat flux.

Classical theory is in good agreement with the measured spectrum ($\lambda_{ei}/L_T = 6 \times 10^{-3}$).
Measurements at five locations in the corona provided high-quality Thomson-scattering data.
Using classical (SH) theory, the Thomson-scattering spectra were used to determine the electron temperature, density, and heat flux ($\lambda_{ei}/L_T$) at all five locations.

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>$T_e$ (keV)</th>
<th>$n_e$ ($\times 10^{19}$ cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>1.27</td>
<td>8.4</td>
</tr>
<tr>
<td>1200</td>
<td>1.21</td>
<td>6.7</td>
</tr>
<tr>
<td>1300</td>
<td>1.16</td>
<td>5.5</td>
</tr>
<tr>
<td>1400</td>
<td>1.14</td>
<td>3.9</td>
</tr>
<tr>
<td>1500</td>
<td>1.12</td>
<td>2.6</td>
</tr>
</tbody>
</table>

$\lambda_{ei}/L_T$ values:
- 1100 µm: $2.5 \times 10^{-3}$
- 1200 µm: $2.5 \times 10^{-3}$
- 1300 µm: $2.8 \times 10^{-3}$
- 1400 µm: $5 \times 10^{-3}$
- 1500 µm: $6 \times 10^{-3}$

SH: Spitzer–Härm
Measurements of electron temperature, density, and $\lambda_{ei}/L_T$ were obtained using classical theory (SH)
Temperature and density profiles were used to infer the classical thermal flux

Heat flux inferred by temperature and density profiles violate classical theory ($\lambda_{ei}/|L_T| > 7 \times 10^{-3}$).
When $\lambda_{ei}/|L_T| > 7 \times 10^{-3}$, there are noticeable discrepancies between the flux inferred from the measured plasma conditions ($q_{SH} = -\kappa \nabla T_e$) and the measured Thomson-scattering spectra.

Nonlocal electron distribution functions that maintain the measured plasma profiles are required when $\lambda_{ei}/|L_T| > 7 \times 10^{-3}$. 
Fokker–Planck calculations,* which include the relevant nonlocal thermal transport physics, were used to determine electron distribution functions consistent with the measured plasma conditions.

\[
\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f = \left( \frac{\partial f}{\partial t} \right)_c
\]

\[
f(t, x, \mathbf{v}) = \sum f_n(t, x, \mathbf{v}) P_n(\Theta)
\]

Fokker–Planck calculations extended the electron distribution function to higher-order terms; nine terms were required to accurately resolve the electron distribution functions at high velocities.

Fokker–Planck calculations,* which include the relevant nonlocal thermal transport physics, were used to determine electron distribution functions consistent with the measured plasma conditions.

Electron distribution functions were determined at each measurement location.

Fokker–Planck electron distribution functions recovered the amplitude of observed scattering features at all positions.

The excellent agreement between calculated and measured spectra provided a path to measure heat flux.
In the most nonlocal conditions, the calculated spectra reproduce the amplitude of the scattering peaks, but underestimate the width.

Spectra calculated using multiple heat-flux models at the most collisional location (1500 µm) show good agreement with the data.
The SNB* model is a computationally efficient method that uses multigroup diffusion to calculate nonlocal heat flux.

\[ q(\vec{r}) = q_{\text{SH}}(\vec{r}) - \sum_g \frac{\lambda_g(\vec{r})}{3} \nabla H_g(\vec{r}) \]

\[ H_g(\vec{r}) = \int_{4\pi} q_g(\vec{\Omega}, \vec{r}) d^2\vec{\Omega} \]

The SNB model overestimates the heat flux at all measured locations.

\[^*\text{G. P. Schurtz, Ph. D. Nicolaï, and M. Busquet, Phys. Plasmas 7, 4238 (2000).}\]
The measured heat flux is reduced from values predicted by classical theory in the nonlocal regions and agrees with classical theory in small-gradient regions.

These results highlight the need to include physics often missing from computationally efficient models (i.e., high-order polynomials to properly resolve velocity space.)
Summary/Conclusions

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