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Remembering Akira Hasegawa at Columbia University: Building Dipoles for Physics and Fusion

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Shortly after returning to Bell Laboratories in 1968, Akira Hasegawa became an adjunct professor at Columbia University and a source of inspiration and ideas to Columbia's plasma physics research program. I arrived at Columbia in the summer of 1985 and had the pleasure of meeting with him nearly every week.

By 1985, excitement in the pursuit of fusion energy science was full-swing. Our laboratory founder, Robert Gross, has just published his textbook *Fusion Energy*, which highlighted STARFIRE: a conceptual design for a steady-state commercial tokamak power plant [1]. In 1984, Troyon and Gruber announced their semi-empirical tokamak beta limit [2], Wagner and colleagues at ASDEX discovered the H-Mode [3], and Greenwald and colleagues at Alcator C succeeded in reaching Lawson's breakeven requirement [4]. These discoveries were driving world-wide excitement in fusion plasma physics.

Hasegawa's best-known research at Bell Laboratories concerned fundamental wave phenomenon relevant to magnetospheric plasmas [5,6] and to nonlinear processes relevant to plasma turbulence [7]. His reputation in space plasma physics created a perfect opportunity to build a bridge between the physics of space to the challenges of fusion energy. On January 24, 1986, Hasegawa was invited to participate in Voyager 2's "flyby" with the planet Uranus. The plasma magnetosphere of Uranus had near unity beta, peaked pressure profiles, and fluctuations driven by the solar wind drove energetic plasma *inward*, which energized the plasma particles [8].

In 1987, following the Voyager 2 encounter, Hasegawa proposed confining a high-temperature plasma by a levitated superconducting dipole magnet as an innovated fusion energy device [9]. The magnetic field is axisymmetric, eliminating neoclassical transport. The plasma pressure is limited by a gradient, allowing unity plasma beta provided that plasma is sufficiently large. Instead of the usual toroidal fusion device, where a large superconducting magnet confines a smaller high-temperature plasma, the dipole reactor is "inside-out": a large toroidal plasma is confined by a very small superconducting ring. Hasegawa's invention illustrated how physics learned from space observations could inform fusion energy research.

Hasegawa's dipole confinement concept led to two successful demonstrations of high-pressure plasma confinement: at the Levitated Dipole Experiment (LDX) built by a joint Columbia University and MIT research team and at the "Ring Trap-1" device built at the University of Tokyo. In addition, a smaller experiment built with a mechanically supported dipole magnet was built at Columbia University for basic studies of turbulence and energetic particle transport.

This presentation will focus on the science discoveries from the Columbia University's "Collisionless Terrella Experiment" and from the joint Columbia-MIT experiment with a strong levitated dipole, called "Levitated Dipole Experiment." These experiments established the conditions for chaotic radial transport [10], nonlinear frequency chirping [11] centrifugal interchange instability [12], inward [13] and outward [14] turbulent transport, and the robust production of high plasma beta with broad profiles characteristic of Hasegawa's 1987 invention [15].

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