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研究課題名（和文） Galactic Outflow Production of Multiphase Gas in the Circumgalactic Medium

研究課題名（英文） Galactic Outflow Production of Multiphase Gas in the Circumgalactic Medium

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研究成果の概要（和文）：天の川銀河のような大きな典型的銀河が形成される時期に、そのハローに数多く存在する衛星矮小銀河からの銀河アウトフローが、重元素を含む様々な状態のガスを生み出す可能性を数値計算で示した。数値計算の結果、衛星矮小銀河における超新星爆発タイプIIとタイプIaによるアウトフローが相互作用し、薄い、フィラメント状の冷却したガス雲を連続的に生み出すことがわかった。大きな銀河のハロー内に数多くある、冷たい高密度MgII吸収線雲を説明できるのではないかと提案する。また、これらの周りに大きく広がるガス雲が、当時の背景紫外線輻射によりイオン化され、CIVやOVI吸収線で観察されるガス雲を生み出しているようだ。

研究成果の学術的意義や社会的意義
銀河の進化の延長に私たち人間の進化がある。よって銀河の進化の探究は人間の存在、その意義の探求に繋がる。
爆発的星形成による銀河アウトフローは銀河円盤から吹き出し、遠く離れた銀河周辺域から銀河間空間にまで到達することもある。吹き出したトンネルを通り、エネルギーや放射が脱出しガスを温めイオン化する。重元素もばら撒かれる。よって、銀河アウトフローは銀河の形成や進化に大きな影響を与えていると考える。銀河周辺域に多く形成されるであろう衛星矮小銀河からの銀河アウトフローが、銀河周辺域のガスの状態を管理し、銀河の進化に影響を与えているという仮説を探求し、様々な可能性を示した点に本研究の意義があったと考える。

研究成果の概要（英文）：Our simulations of galactic outflows from dwarf satellite galaxies highlight the possible roles of galactic outflows producing multiphase, metal-enriched gas in the circumgalactic medium surrounding large, luminous galaxies like the Milky Way galaxy. We find that SNII and SNIa driven outflows interact and continuously generate thin, filamentary cooled gas that are responsible for the observed weak MgII absorbers. They are also surrounded by larger, more diffuse gas that produce CIV and/or OVI absorption in the presence of the UV metagalactic radiation at high redshift. The global importance of dwarf galactic outflows will be addressed in more general simulations.

研究分野： 天文学

キーワード： circumgalactic medium　galactic outflows　numerical simulations

１．研究開始当初の背景

Analysis of metal absorption line observations by our research collaborators [1][2][3] reveals the extended presence of multiphase gas in the CGM. Numerous, compact (1~100 pc), low-ionization gas clouds are traced by weak MgII lines. They have near-solar to super-solar metallicities, and some of them are even iron enhanced in relation to α elements, even though luminous galaxies are rarely found within a ~50 kpc impact parameter. The origin and nature of such observed low-ionization absorbers remain unclear, and in fact, no numerical simulations have addressed such questions before our study.

２．研究の目的

Our goal is to understand the origin and nature of weak MgII clouds and the surrounding coronal gas in the halos of $L*$ galaxies at intermediate redshift. Observations at intermediate redshifts reveal the presence of numerous, compact, weak Mg II absorbers with near to super-solar metallicities, often surrounded by more extended regions that produce C IV and/or O VI absorption, in the circumgalactic medium at large impact parameters from luminous galaxies. In our study, we test the hypothesis that undetected, satellite dwarf galaxies are responsible for producing some of these weak Mg II absorbers as well as surrounding CIV and OVI absorbers, using gas dynamical simulations of galactic outflows from a dwarf satellite galaxy which could form in a larger $L*$ halo at $z = 2$.

３．研究の方法

(1) We use the adaptive mesh refinement hydrodynamics code Enzo [4] to simulate repeated supernova explosions in the disk of a dwarf galaxy. We solve the equations of hydrodynamics using a direct Eulerian piecewise parabolic method [4][5] and a two-shock approximate Riemann solver with progressive fallback to more diffusive Riemann solvers in the event that higher order methods produce negative densities or energies. Our simulation box has dimensions, (6.5536,6.5536, 32.768) kpc, initially with (32, 32, 160) cells. Only half the galactic disk above its midplane is simulated. We refine cells to resolve shocks with a standard minimum pressure jump condition [5] and to resolve cooling at turbulent interfaces where the sound crossing time exceeds the cooling time. We use 4 refinement levels resulting in a highest resolution of 12.8 pc. We also ran the same simulation with 3 refinement levels as a comparative resolution study, and by applying 6 refinement levels in a region where Mg II filaments form in order to test the effects of resolution on fragmentation.

(2) We model a dwarf galaxy at redshift $z = 2$ with a halo mass (4×10^9 Msun), and a virial radius (17.3 kpc). This model has a disk gas mass (5.2×10^8 Msun). We adopt a Burkert [6] dark matter potential with a core radius (848 pc) and central density (1.93×10^{-23} g/cm^3). The gas is described as a softened exponential disk [7] with temperature varying between 10^3 K and a few ×10^4 K, and the maximum circular velocity of 48.8 km/s. Our model galaxy is placed in a static halo background with 1.83×10^{-28} g/cm^3with an initial metallicity of $Z = 0.001$ and a molecular weight $\mu = 0.6$.

(3) We use radiative cooling functions used in our simulations as a function of temperature from [8] or $T \geq 10^4$ K for different metallicities and from [9] for $T < 10^4$ K for solar metallicity.

(4) We use Stellar Yields for Galactic Modeling Applications (SYGMA) [10] to model the chemical ejecta and feedback from simple stellar populations. The metals produced by SNIIs and SNIas are followed and advected separately.

(5) We use the TRIDENT analysis tool [11] to calculate the ionization fractions of the species of interest based on the cell-by-cell density, temperature, and metallicity.

４．研究成果

Our results highlight the possibility of dwarf galactic outflows producing transient, but continuously generated Mg II clouds, as well as larger C IV and O VI clouds, in sub-LLS and Lyα forest environments.

(1) Thin, filamentary, weak Mg II absorbers are produced in two stages: Phase 1: shocked SNII-enriched gas loses energy and descends toward expanding SNII-enriched gas and is shocked, cools, and fragments, and Phase 2: SNIa-driven outflow gas shocks the SNII-enriched gas as well as phase 1 shells, which then cool and fragment. The width of the filaments and fragments are <100 pc with our standard numerical resolution. A single Mg II cloud survives for ~ 60 Myr, but we suggest Mg II absorbers will continuously be produced through cycles of phase 1 and phase 2 formation for > 150 Myr by repeated bursts of star formation. see Figure 1.

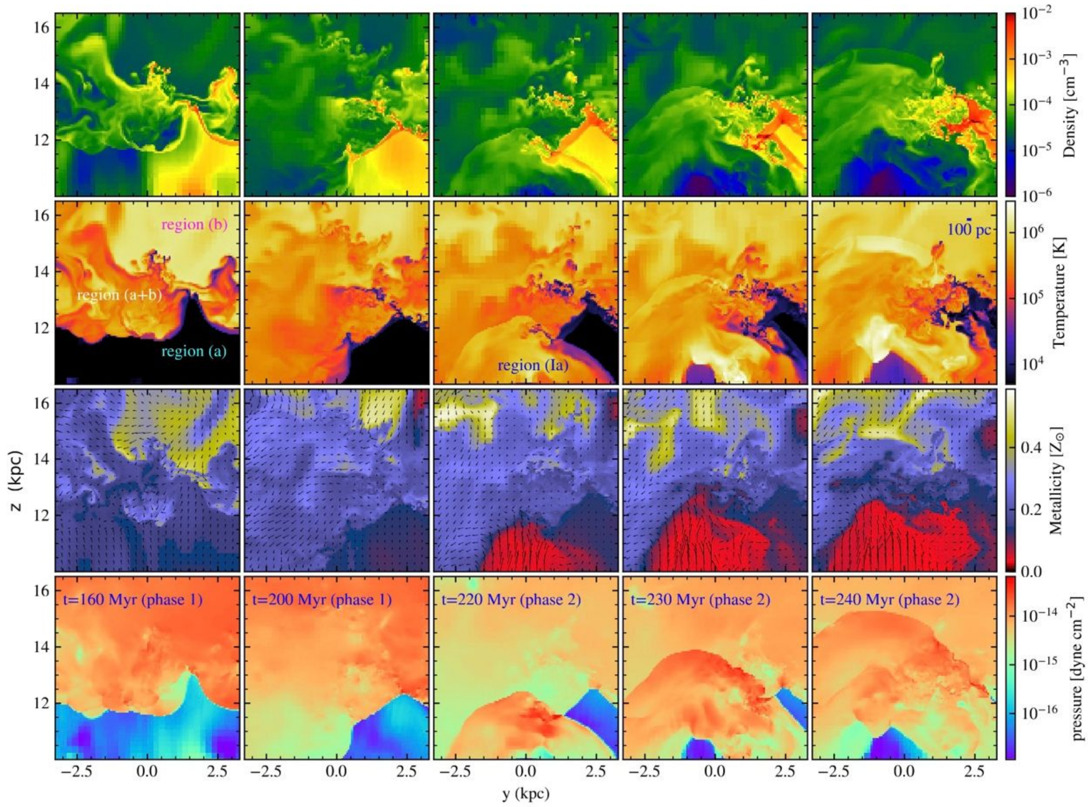

Figure1: Sliced density, temperature, metallicity, and pressure (from top to bottom) distributions of cool, dense clouds at x = +1.42 kpc from the disk center in y-z plane at phase 1 (t =160 and 200 Myr) and phase 2 (t = 220, 230, and 240 Myr) from left to right. Phase 1 formation begins when descending shocked SNII-enriched gas (region b) collides with the expanding SNII-enriched gas (region a) at the inner shock front, and phase 2 formation begins when SNIa-driven outflow (region Ia) rams into the rest of the SNII-enriched gas and the clouds made at phase 1. The arrows in the metallicity figures show the direction of gas flow with v_max = 429 km/s.

(2a) C IV absorbers are produced in expanding SNII enriched gas and shocked SNII-enriched gas. CIV absorbers in the expanding SNII-enriched gas extend over 1–4 kpc and C IV absorbers in the shocked SNII-enriched gas are smaller, 0.5–1 kpc, but they are both cool and photoionized. The smaller C IV absorbers originate from the same clouds that produce weak Mg II absorbers, and they surround the dense Mg II clouds. As the clouds get destroyed and mixed with the surrounding gas, Mg II absorbers disappear first, but C IV absorbers survive for another 20–30 Myr.

(2b) O VI absorbers are also produced in expanding SNII-enriched gas and shocked SNII-enriched gas. O VI absorbers in the expanding SNII-enriched gas originate from the same cool clouds that produce C IV absorbers, but O VI absorbers in the shocked SNII-enriched gas are not coincident with

Mg II absorbers or C IV absorbers. Their sizes are ~>1 kpc.

(2c) C IV absorbers and most O VI absorbers are cool, photoionized clouds while O VI absorbers arising in swept-up shells in region (b) are hotter and collisionally ionized. Photoionization dominates in sub-LLS and Lyα environments found in our models. see Figure 2 & 3.

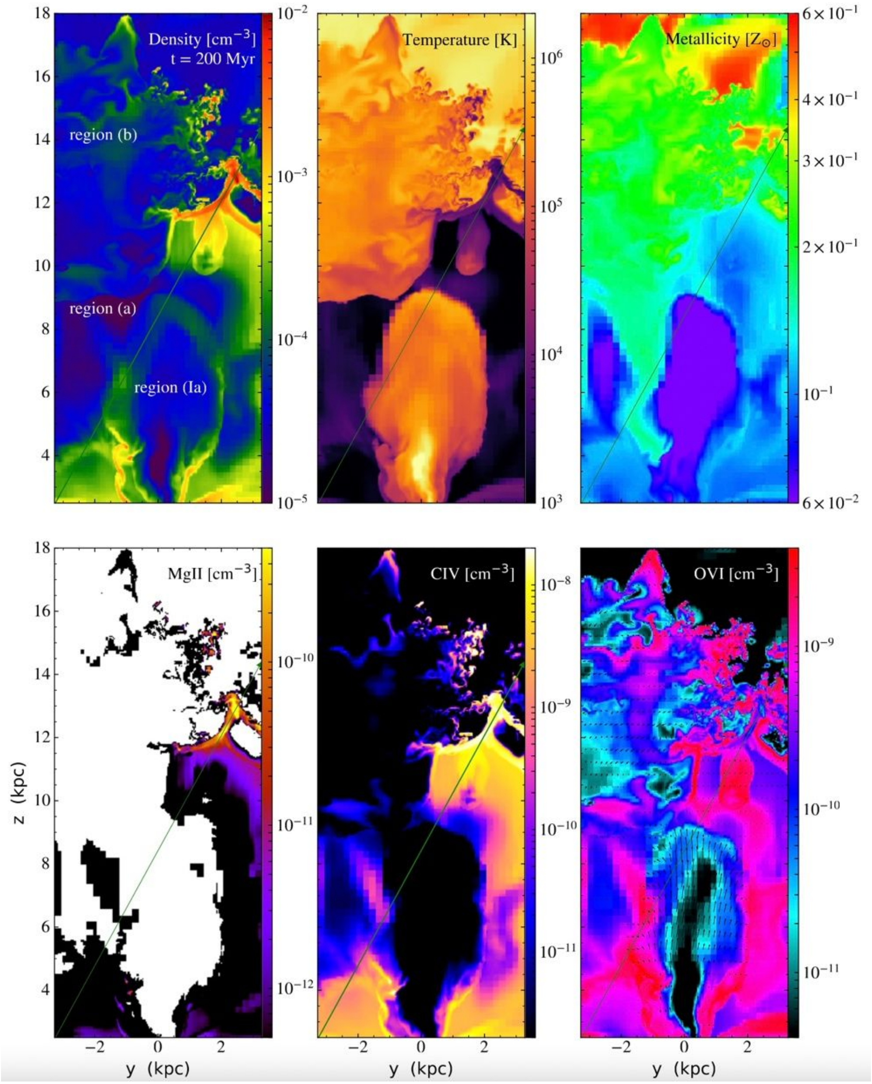

Figure 2. Sliced density, temperature, metallicity (top from left to right), and Mg II, C IV, and O VI (bottom from left to right) density distributions at x=+1.92 kpc from the disk center in the y-z plane, at t =200 Myr. A line of sight from [x,y,z]=[+1.92 kpc, -3.28 kpc, +2.45 kpc] to [+1.92 kpc, +3.28 kpc, +14.4 kpc] is shown by a green line . The arrows in the bottom right figure show the direction of the gas flow with vmax=353 km/s.

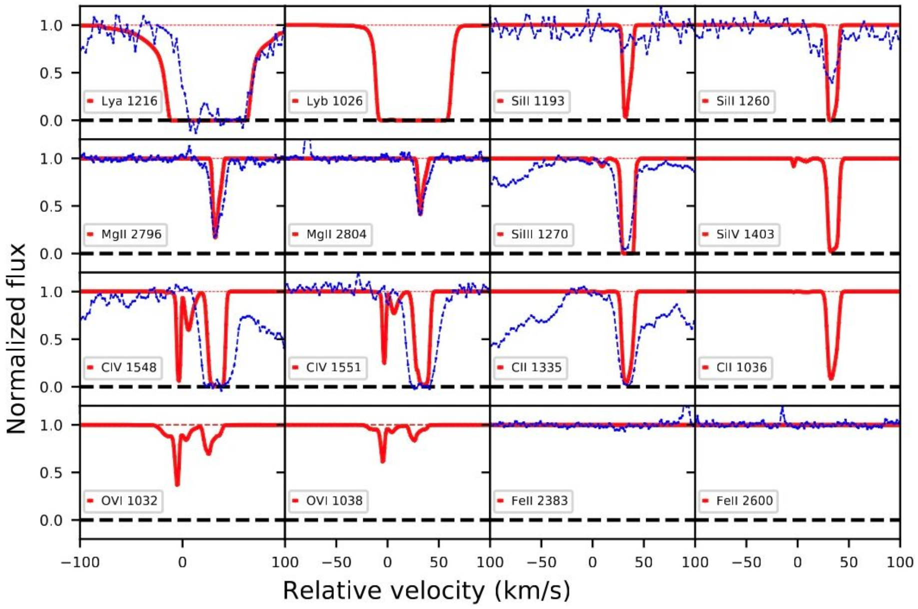

Figure 3. Mock spectra along the line of sight (green line in Figure 6) at t =200 Myr, compared to the observed profiles of system 3 at z =1.75570 (blue dashed line, Misawa et al. 2008) [2]. They are convolved with the instrumental line-spread function (R = 45, 000) consistent with the observation.

(3) The metallicities of Mg II, C IV, and O VI absorbers are Z = 0.1–0.2Zsun by t =∼ 200–300 Myr, after one moderate nuclear starburst forms in a dwarf disk and halo with a low initial metallicity Z = 0.001Zsun. We speculate that the clouds forming in shocked outflow gas will be progressively enriched with more metals when bursts of star formation are repeated. See Figure 4.

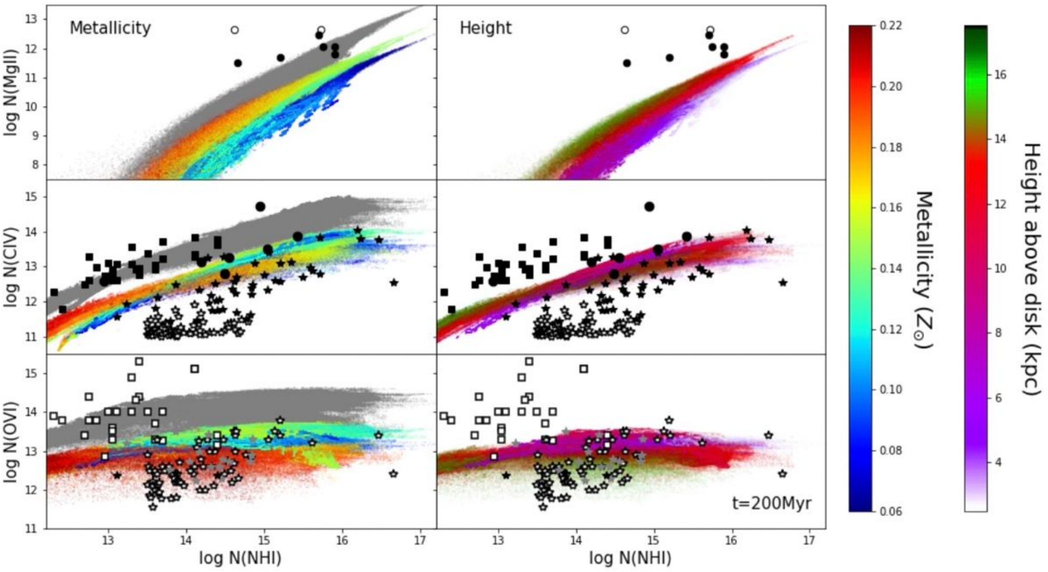

Figure 4. Mg II (top row), C IV (middle row), and O VI (bottom row) versus H I column densities in sightlines parallel to each of the three cardinal axes at t =200 Myr with different colors indicating Mg II, C IV, and O VI density-weighted metallicities (left column) and height above the disk (right column), to be compared to the observed Mg II/C IV clouds by Misawa et al. 2008 (circle) [2] and the observed C IV/O VI observations by Schaye et al. 2007 (square) [12] and D'Odorico et al. 2016 (star, but gray star for detection of only one member of the doublet) [13]. Note O VI densities from Schaye et al. 2007 (open square) and C IV and O VI densities from D'Odorico et al. 2016 (open star) are upper limits (open square). Grey points indicate ion versus H I column density distributions expected when all the gas in our simulation is assumed to have solar metallicity. The system 3 at z =1.7557 toward HE2243-6031 Misawa et al. (2008) could have a very large metallicity, Z > 7.9 Z , or a moderate value, ∼ 1.0Z , depending on two different phoionization models (open circle).

(4) The covering fraction of weak Mg II absorbers in our dwarf halo is > 3–6%. This is a lower limit as it represents the effects of only one moderate nuclear starburst, and more than half the metal-enriched gas leaves the simulation box before the end of the run. To reproduce the observed estimate for the covering fraction in a L∗ halo (30%) with outflows from such galaxies alone, sightlines must go through haloes of multiple dwarf satellite galaxies. We also speculate that the covering fraction in a single dwarf halo will be boosted with repeated bursts with many cycles of phase 1 and phase 2 formation in a large simulation box that covers the entire halo.

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５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　1件／うちオープンアクセス　1件）

１．著者名 Fujita Akimi、Misawa Toru、Charlton Jane C.、Meiksin Avery、Low Mordecai-Mark Mac	４．巻 909
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〔学会発表〕　計4件（うち招待講演　1件／うち国際学会　0件）

１．発表者名 Akimi Fujita
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１．発表者名 Akimi Fujita
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

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８．本研究に関連して実施した国際共同研究の実施状況

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米国	American Museum of Natural History	Center for Computation Astrophysics	Pennsylvania State University	
英国	Univeristy of Edinburgh			