The Dynamic Proto-atmospheres around Low-mass Planets with Eccentric Orbits

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Abstract

Protoplanets are able to accrete primordial atmospheres when embedded in the gaseous protoplanetary disk. The formation and structure of the proto-atmosphere are subject to the planet–disk environment and orbital effects. In particular, when planets are on eccentric orbits, their velocities relative to the gas can exceed the sound speed. The planets generate atmosphere-stripping bow shocks. We investigate the proto-atmospheres on low-mass planets with eccentric orbits with radiation-hydrodynamics simulations. A 2D radiative model of the proto-atmosphere is established with tabulated opacities for the gas and dust. The solutions reveal large-scale gas recycling inside a bow shock structure. The atmospheres on eccentric planets are typically three to four orders of magnitude less massive than those on planets with circular orbits. Overall, however, a supersonic environment is favorable for planets to keep an early stable atmosphere, rather than harmful, due to the steady gas supply through the recycling flow. We also quantitatively explore how such atmospheres are affected by the planet’s velocity relative to the gas, the planet mass, and the background gas density. Our time-dependent simulations track the orbital evolution of the proto-atmosphere with the planet–disk parameters changing throughout the orbit. Atmospheric properties show oscillatory patterns as the planet travels on an eccentric orbit, with a lag in phase. To sum up, low-mass eccentric planets can retain small proto-atmospheres despite the stripping effects of bow shocks. The atmospheres are always connected to and interacting with the disk gas. These findings provide important insights into the impacts of migration and scattering on planetary proto-atmospheres.

Unified Astronomy Thesaurus concepts: Hydrodynamics (1963); Planetary atmospheres (1244); Planet formation (1241); Elliptical orbits (457)

1. Introduction

Protoplanets are generally believed to form before the gas in their parent nebulae dissipates and are therefore likely to capture proto-atmospheres from the nebula gas (e.g., Goldreich et al. 2004; Lee et al. 2014). Such proto-atmospheres should resemble the solar nebula in composition—rich in hydrogen and helium.

Early pioneering work by Mizuno et al. (1978) and Mizuno (1980) explored the formation of Jupiter-like gas giants by accreting nebula gas. The core accretion theory (e.g., Safronov 1969; Perri & Cameron 1974; Mizuno et al. 1978; Stevenson 1982; Pollack et al. 1996) focused on how accumulation of nebula gas onto protoplanets can trigger runaway accretion when the accreted solid and gas masses are comparable, and typically after the mass of the core reaches the critical value (∼10 M⊕, Venturini et al. 2015). Only in recent years has the discovery and characterization of exoplanets revealed the ubiquity of low-density super-Earths and mini-Neptunes (e.g., Borucki et al. 2010; Batalha et al. 2013; Fressin et al. 2013). Analyses show that they can retain the primordial H2/He atmospheres (Weiss & Marcy 2014; Rogers 2015), likely 0.1%–10% by mass (Lopez & Fortney 2014), although there are exceptions (Espinoza et al. 2016). This has raised interest in the community to understand how lower-mass planets (≪5 M⊕) accrete and retain proto-atmospheres.

From an astrobiological point of view, the bioessential elements C, H, O, and N in the solar nebula mostly resided in volatile phases, e.g., H2, H2O, CO/CO2, or N2 (Lodders & Katharina 2003). Terrestrial water may be attributable to H2O accreted from the nebula, or H2O produced as H2 in the proto-atmosphere that reacted with iron oxides (e.g., Ikoma & Genda 2006; Wu et al. 2018; Williams et al. 2019). A proto-atmosphere may also have supplied Earth with noble gases (e.g., Mizuno et al. 1980; Wu et al. 2018; Sharp & Olson 2019). Modeling the formation of a planet’s proto-atmosphere is required to assess its geochemistry and habitability.

A number of studies have performed detailed calculations on the accretion of nebula-originated primordial atmospheres onto low-mass planets (e.g., Lammer et al. 2014; Lee et al. 2014; Ginzburg et al. 2015; Lee & Chiang 2015; Stökl et al. 2015, 2016; Kuwahara et al. 2019), indicating that Earth-size planets can acquire an H2/He proto-atmosphere with surface pressure up to 103 bar. Sophisticated hydrodynamics codes have been adopted to solve the detailed structure of the atmospheres. Ormel et al. (2015a, 2015b) conducted hydrodynamic simulations to solve an isothermal proto-atmosphere around Earth-like planets in 2D and 3D, respectively. The subsequent work by Cimerman et al. (2017) included radiation transport and opacity treatment to consider radiative cooling. These studies revealed the rotation and recycling behaviors of atmospheric gas around the planet, which might prevent low-mass planets from runaway gas accretion.

So far, numerical studies on proto-atmospheres have been focused on planets orbiting their host stars on circular orbits. In particular, ideal spherical symmetry is assumed in 1D simulations by definition to simplify the physics (Stökl et al. 2015, 2016). However, protoplanets are not always on circular orbits, especially in young planetary systems. Exoplanet
discoveries have revealed how common it is for planets to migrate, often stochastically, due to resonances, close encounters, or planet–planet scattering (e.g., Chiang & Murray 2002; Ford & Rasio 2008; Raymond et al. 2008; Michtchenko et al. 2013; Petrovich et al. 2014). To date, many exoplanets have been found on eccentric orbits ($e > 0.1$), regardless of their mass and sizes (e.g., Tremaine & Zakamska 2004; Wittenmyer et al. 2013, 2019; Antoniadou & Voyatzis 2015; Kane et al. 2016). In our solar system, Mars is hypothesized to have been scattered from $\sim 1$ au to an eccentric orbit before settling into its present orbit at $\sim 1.5$ au (Hansen 2009); and the presence of an ice giant on a very elliptical orbit scattered from $\sim 10$ au has been hypothesized (Thommes et al. 1999; Nesvorný & David 2011) and inferred in observations as the putative Planet Nine (Batygin & Brown 2016). The orbital velocity of a planet or protoplanet on an eccentric orbit will differ significantly from that of the surrounding gas, which remains on circular orbits with approximately the Keplerian speed. Eccentric planets can strongly disturb the nebular gas and even the background magnetic fields (Mai et al. 2018). It is unclear how such relative motions between the planet and the gas will change the gas dynamics. Planets on slightly eccentric orbits may accrete gas faster, while planets on more eccentric orbits (e.g., moving supersonically relative to the gas) generate a bow shock that can fundamentally change how it accretes—or loses—a proto-atmosphere. In fact, the relative motion between the planet and the gas becomes supersonic throughout the orbit once the eccentricity reaches $\sim 0.08$ (assuming the planet is 1 au away from the star, see Figure 1).

Despite the importance of these orbital effects, there have been no numerical models that have considered the implications of eccentric orbits for the presence of proto-atmospheres. In this work, we investigate how planets on eccentric orbits retain proto-atmospheres, particularly when traveling supersonically through the gas and producing bow shocks. We aim to address the following questions.

1. How does the proto-atmosphere interact with nebula gas when the planet is moving through the disk supersonically?
2. What is the flow structure around the planet? How much gas can the planet hold?
3. How sensitive is the proto-atmosphere to the disk environment and the planet mass?
4. How does the proto-atmosphere evolve throughout an eccentric orbit? Does the planet’s atmosphere gain and lose gas periodically?

The paper is organized as follows: Section 2 describes the setup of the hydrodynamic simulation, including the equations for radiation hydrodynamics (Section 2.1), the physical and numerical setup (Section 2.2), and the list of simulations preformed in this study (Section 2.3). In Section 3 we present the simulation results of our canonical setup (Section 3.1), the variations with different disk and planet properties (Section 3.2), and the temporal evolution throughout the orbit (Section 3.3). We discuss the findings in Section 4 and summarize the study in Section 5.

2. Hydrodynamic Simulations

2.1. Problem Setup and Equations

Proto-atmosphere formation on planets with eccentric orbits ($e \geq 0.1$) can be modeled as a gravitating spherical object moving supersonically in the inviscid, compressible, and homogeneous gas. In this study, we include radiation transport of energy and assume the disk gas to be an ideal gas. We adopt the assumption of local thermal equilibrium and the linear two-temperature approach for the flux-limited diffusion (FLD) approximation for radiation transfer (Kuiper et al. 2010; Kuiper & Hosokawa 2018). For convenience, we adopt a frame comoving with the planet in all simulations. The planet object is placed in a wind tunnel instantaneously at the beginning and the subsequent gas evolution is simulated using a radiation-hydrodynamics model until a steady/quasi-steady state is reached.

The problem can be studied with sophisticated hydrodynamics codes (e.g., PLUTO, see Section 2.2) solving the Euler’s equations representing the conservation of mass, momentum, and energy:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (1)$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) + \nabla P = \rho \mathbf{a}_{\text{ext}} \quad (2)$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P) \mathbf{v}] = \rho \mathbf{v} \cdot \mathbf{a}_{\text{ext}} \quad (3)$$

where $\rho$ is the mass density of the gas, $\mathbf{v}$ is the relative velocity between the planet and the gas, $P$ is the gas pressure, $\mathbf{a}_{\text{ext}}$ is the acceleration caused by external forces, $E = E_{\text{int}} + E_{\text{rad}} + E_{\text{kin}}$ is the total energy density of the gas, which is the sum of internal energy density ($E_{\text{int}} = c_v \rho T$, where $c_v$ is the heat capacity at constant volume, $T$ is gas temperature), radiation energy density ($E_{\text{rad}} = a T^4$, $a$ is the

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6 The two-temperature approach solves for the radiation energy density as well as for the internal gas temperature at the same time, with gas temperature and radiation temperature treated separately.
radiation constant), and kinetic energy density \(E_{\text{kin}} = (1/2)\rho v^2\).

With operator splitting we separately solve the transport term \(\nabla (E \vec{v})\), leaving the time derivatives of the internal and radiation energy density as in Kuiper et al. (2010) and Cimerman et al. (2017):

\[
\frac{\partial (E_{\text{int}} + E_{\text{rad}})}{\partial t} = - \nabla \cdot \vec{F} - P \nabla \cdot \vec{v}
\]

where \(\vec{F}\) is the flux of radiation energy density. Substituting \(E_{\text{int}}\) by \(c_v \rho T\) and \(E_{\text{rad}}\) by \(\alpha T^4\), we have

\[
\frac{\partial E_{\text{rad}}}{\partial t} = - \left(\frac{c_v \rho}{4 \alpha T^3} + 1\right)^{-1} (\nabla \cdot \vec{F} + P \nabla \cdot \vec{v})
\]

and from the FLD approximation

\[
\vec{F} = - \frac{\lambda c}{\rho \kappa_R} \nabla E_{\text{rad}}
\]

where \(\lambda\) is the flux limiter following the choice in Levermore & Pomraning (1981), \(c\) is the light speed, and \(\kappa_R\) is the Rosseland mean opacity.

Note that the above calculations do not include irradiation from the central planet because the external sources of luminosity from the planet surface (due to radiogenic heat and/or accretion of planetesimals) are negligible in our setup. The heat generated by accretion of planetesimals with a mass accretion rate of \(10^{-7} M_{\oplus}\) yr\(^{-1}\) (Stökl et al. 2015) is three to four orders of magnitude lower than that from gas accretion in our models \((M_{\oplus}\) is the planet mass\). The radiogenic energy with a reference level of \(10^{11}\) erg s\(^{-1}\) M\(^{-1}\) (for early Earth, Stacey & Davis 2008) is at least two additional orders of magnitude lower (Stökl et al. 2015). For a more detailed analysis of the FLD approximation in radiation transport please refer to Kuiper et al. (2010).

The external forces considered in the gas system include the gravity from the planet object:

\[
a_{\text{ext}} = -\frac{GM_{\oplus}}{r^2} \vec{e}_r
\]

where \(G\) is the gravitational constant and \(r\) is the distance to the center of the planet. Following Cimerman et al. (2017), we do not consider ionization or dissociation of molecules as we focus on solving the flow structure and bulk atmospheric properties. In fact, the models in Desch & Connolly (2002) and Morris & Desch (2010) found that \(\approx 7\%\) of \(H_2\) in nebular shocks can be dissociated, but the total energy of the gas remains unchanged. The radiative forces are neglected because they are small compared to gravity from the planet and the gas pressure.

The set of Euler’s equations (Equations (1), (2), and (3)) is closed by the perfect-gas equation of state:

\[
P = (\gamma - 1) E_{\text{int}} = \frac{\rho}{\mu m_{\text{H}}} k_{\text{B}} T
\]

where \(\gamma\) is the adiabatic index, which we fix as \(7/5\) (for molecular hydrogen) throughout the simulations. \(\mu\) is the mean molecular weight, for which we adopt a constant value of 2.353, corresponding to the gas of solar metallicity. \(k_{\text{B}}\) is the Boltzmann constant and \(m_{\text{H}}\) is the mass of a hydrogen atom.

The initial values of \(\rho, P,\) and \(v\) of gas in the wind tunnel are set as \(\rho_{\infty}, P_{\infty},\) and \(v_{\infty},\) the same as the properties of unperturbed disk gas far away from the planet. The Mach number is defined as \(M = v_{\infty}/c_{\infty},\) where the sound speed of the disk is \(c_{\infty} = \sqrt{T_{\infty}/\rho_{\infty}}.\)

### 2.2. The Model and Numerics

#### 2.2.1. The Grid

The simulations in this work are performed using the open-source high-order Godunov-type hydrodynamics code PLUTO (version 4.1) (Mignone et al. 2007), coupled with a module MAKEMAKE solving radiation transport with the FLD approximation (Kuiper et al. 2010). We use the second-order Runge–Kutta (RK2) time-stepping scheme, a van Leer flux limiter in the reconstruction step and a Harten–Lax–van Leer solver to solve the Riemann problem. With MAKEMAKE the FLD equation, Equation (6), is solved with a generalized minimal residual (GMRES) solver, first developed by Saad & Schultz (1986).

We adopt a 2D axially symmetric spherical grid \((r, \theta)\) and place the planet object at the origin of the coordinates. The spherical geometry is proven more natural to the problem setup and yields more accurate solutions to the expected structure of the atmosphere (Ormel et al. 2015a). The computational domain expands from 1 to 1000 radii of the planet with 538 cells in the \(r\) direction and from 0 to \(\pi\) with 250 cells in the \(\theta\) direction. The direction of the pole points to \(\theta = 0\). We use logarithmic spacing for the cells in the radial dimension to obtain a higher resolution in the proximity of the planet, where the majority of the proto-atmosphere is located.

#### 2.2.2. Boundary and Initial Conditions

The boundary conditions of the computational domain are similar to those in Thun et al. (2016). The inner radial boundary of the domain is set as reflective so that no mass or radiation is transported through the planet surface. The outer radial boundary condition is configured according to where the gas flows in and out of the domain. When \(0 \leq \theta < \pi/2\), we use the inflow boundary condition to set the ghost cells with the unperturbed gas values. When \(\pi/2 \leq \theta \leq \pi\), a zero-gradient condition is implemented instead to ensure the values of the ghost cell stay the same as the boundary cells so no reflections would occur. We adopt axisymmetric boundary conditions for both boundaries in the polar dimension.

We use the well-known “minimum mass solar nebula” (MMSN) model (Weidenschilling 1977; Hayashi 1981; Thrommes & Duncan 2006) to provide the approximate initial values for the gas properties in the unperturbed disk. In our canonical simulation, we set up a planetary object \((M_{\oplus} = 1 M_{\odot}, R_{\oplus} = 1 R_{\odot})\) embedded in the homogeneous disk gas \((T_{\infty} = 300 \text{ K}, \rho_{\infty} = 10^{-9} \text{ g cm}^{-3})\) located approximately at \(a = 1 \text{ au}\) from the Sun. The velocity of the planet relative to the gas \(v_{\infty}\) is set as 4.8 km s\(^{-1}\) (or \(M = 3.93\)). Planets with orbital eccentricities between 0.17 and 0.35 are able to reach this velocity at certain positions in their orbits. Adopting values provided from different disk models would slightly alter the background density for the location of the planet. For example, the updated MMSN model (Desch 2007) would increase the nebular density at 1 au by 1–1.5 orders of magnitude, while the “minimum mass extrasolar nebula” (Chiang & Laughlin 2013; Lee et al. 2014) would increase it by 0.5–1 orders of magnitude. These variations are within the...
More accurately, the density profile of the background gas medium follows an approximated vertical hydrostatic stratification structure for protoplanetary disks (e.g., Armitage 2010):

$$\rho_\infty(z) = \rho_\infty \exp\left(-\frac{z^2}{2H^2}\right)$$  \hspace{1cm} (9)

where $z$ is the vertical distance from the midplane, $H = \sqrt{R_Hc_s} / (GM_\ast)$ is the pressure scale height of the disk gas ($R_H$ is the specific gas constant for H$_2$, $M_\ast$ is the solar mass). For simplicity, we do not take into account the vertical density profile but adopt the midplane gas density $\rho_\infty$ as the background value. This is because we concentrate on relatively small planets or planetary embryos (e.g., objects of sub-Earth or Earth size). The radii of these objects (including the proto-atmospheres) are at least four orders of magnitude smaller than $H$ in our simulations.

The initial setup is slightly different in our orbit-dependent simulation (see Section 2.3) because we start the simulation when the planet is at its perihelion. The initial values of gas properties ($\rho_\infty$, $T_\infty$, $P_\infty$, $v_\infty$) are adjusted to match the corresponding disk environment for an orbit with semimajor axis $a = 1$ au and eccentricity $e = 0.2$.

2.2.3. Opacities

As mentioned above, the homogeneous background gas is assumed to have the same composition as the solar nebula. Data for gas opacity are adopted from Malygin et al. (2014). Opacities for lower temperatures (i.e., $T_{\text{gas}} < 700$ K) are extrapolated from the higher-temperature data (see Marleau et al. 2019 for details). We include dust in all simulations with a dust-to-gas mass ratio $\sim 0.01$, assuming "normal" silicates with Fe/(Mg + Fe) = 0.3, as defined in Semenov et al. (2003). Dust grains are simplified as homogeneous spherical particles, and their opacities are taken from corresponding tables in Semenov et al. (2003) without the built-in calculations of dust evaporation. Instead, evaporation of the refractory component in the region of the dust-to-gas transition temperature (1400–1600 K) is modeled separately—we adopt a smooth transition curve to lower temperatures with arctan functions and a steep linear decrease to higher temperatures.

2.3. List of Simulations

The main goal of this work is to explore how an eccentric orbit affects the dynamics and structure of the planetary proto-atmosphere. To achieve this goal and answer the four science questions in Section 1 we carry out a list of simulations with different initial conditions, which can be divided into the "snapshot" simulations and the orbit-dependent simulation (see Table 1).

For the "snapshot" simulations, we set the relative velocity between the planet and disk gas ($v_{\infty}$, or represented by the Mach number $M_\infty$), the planet mass ($M_{\oplus}$), and gas density ($\rho_\infty$) as free input parameters to specify the disk–planet environment. The gas pressure is adjusted to match the gas temperature at 300 K. The simulations are run until they reach steady/ quasi-steady states so that the solutions represent "snapshots" of the proto-atmospheres in the corresponding environments. For the orbit-dependent simulation, we use the planet mass ($M_{\oplus}$), the orbital semimajor axis ($a$), and orbital eccentricity ($e$) as inputs to determine the specific eccentric orbit for the planet. Other parameters such as gas density, pressure, temperature, and relative velocity are determined upon the time-dependent star–planet distance, which in turn is dependent on these input orbital parameters. It is therefore a time-dependent simulation in which we read outputs regularly to track the evolution of the proto-atmosphere throughout the eccentric orbit. Given that these simulations are significantly more expensive in terms of computation hours, we do not perform a parameter study involving full-orbit simulations in this work.

In reality, the orientation of the planetary bow shock is also changing as the planet moves to different locations on the orbit. It is directly determined by the vector difference between the planet orbital velocity ($v_{\text{pl}}$) and the disk gas velocity ($v_{\text{gas}}$) at each location (see Figure 2). Both quantities decrease in magnitude with a larger distance from the star. At perihelion, the planet travels faster than the gas and generates a shock front aligned with $v_{\text{pl}}$. At aphelion, the gas in sub-Keplerian motion is faster and the shock front is in the opposite direction as $v_{\text{pl}}$. As shown in Figure 2, the change of bow shock orientation throughout the orbit is limited (max. $\sim 20^\circ$ for an orbit $e = 0.2$). Because the timescale on which the orientation changes is much longer than the dynamical timescale of gas accretion, the variation of bow shock direction is negligible in the local-framed hydrodynamic simulations.

| Name | $v_{\infty}$ (km s$^{-1}$)/$M_\odot$ | $M_{\oplus}$ ($M_\oplus$) | $\rho_{\infty}$ (g cm$^{-3}$) | Comments |
|------|-----------------------------------|--------------------------|--------------------------|----------|
| Canonical | 4.8/3.93 | 1.0 | 10$^{-9}$ | The canonical case |
| VEL3.2 | 3.2/2.64 | 1.0 | 10$^{-9}$ | Sensitivity study on Mach number/relative velocity |
| VEL3.7 | 3.7/3.02 | 1.0 | 10$^{-9}$ | |
| VEL4.2 | 4.2/3.47 | 1.0 | 10$^{-9}$ | |
| VEL5.3 | 5.3/4.38 | 1.0 | 10$^{-9}$ | |
| VEL5.9 | 5.9/4.84 | 1.0 | 10$^{-9}$ | |
| VEL6.4 | 6.4/5.29 | 1.0 | 10$^{-9}$ | |
| VEL7.0 | 7.0/5.75 | 1.0 | 10$^{-9}$ | |
| VEL7.5 | 7.5/6.2 | 1.0 | 10$^{-9}$ | |
| FM0.1 | 4.8/3.93 | 0.1 | 10$^{-9}$ | Sensitivity study on planet mass |
| FM0.3 | 4.8/3.93 | 0.3 | 10$^{-9}$ | |
| FM0.5 | 4.8/3.93 | 0.5 | 10$^{-9}$ | |
| FM0.7 | 4.8/3.93 | 0.7 | 10$^{-9}$ | |
| FM0.2 | 4.8/3.93 | 2.0 | 10$^{-9}$ | |
| FM3.0 | 4.8/3.93 | 3.0 | 10$^{-9}$ | |
| DEN-7 | 4.8/3.93 | 1.0 | 10$^{-7}$ | Sensitivity study on gas density |
| DEN-8 | 4.8/3.93 | 1.0 | 10$^{-8}$ | |
| DEN-10 | 4.8/3.93 | 1.0 | 10$^{-10}$ | |

| Name | $M_{\oplus}$ ($M_\oplus$) | $a$ (au) | $e$ | Comments |
|------|--------------------------|----------|----|----------|
| ORB | 1.0 | 1.0 | 0.2 | Time-dependent simulation to track orbital evolution |
Figure 2. Schematic of a planet traveling supersonically on an eccentric orbit. The dark gray arrows represent the planet’s orbital velocity ($\mathbf{v}_{\text{pl}}$), tangential to the elliptical orbit. The blue arrows denote the disk gas velocity ($\mathbf{v}_{\text{gas}}$), which is always perpendicular to the direction of the star. The relative velocity between the planet and the gas is the vector difference of the dark gray and blue arrows (the dotted arrows in light red, also shifted to the center of the planet as solid red arrows). Note that the schematic has exaggerated the orbital eccentricity and the planet size. The absolute lengths of all arrows in the schematic have no meaning. Both $|\mathbf{v}_{\text{pl}}|$ and $|\mathbf{v}_{\text{gas}}|$ decrease as the planet gets further away from the star, though $|\mathbf{v}_{\text{pl}}| > |\mathbf{v}_{\text{gas}}|$ from location A to B, or D to A, and $|\mathbf{v}_{\text{pl}}| < |\mathbf{v}_{\text{gas}}|$ from location B to D. The red vectors also represent the orientation of planetary shock fronts (symbolized as light blue dotted curves). Counterintuitively, the orientation of bow shocks does not change significantly throughout the orbit. Given that the orbital timescale is much longer than the dynamical timescale of gas accretion, the change of bow shock orientation is trivial in the local-framed simulations.

3. Results

We present the general 2D flow structure of the bow shock and the proto-atmosphere around the planet in Section 3.1. We conduct a parameter study on the “snapshot” simulations and show how the solutions change with the planet–disk environments in Section 3.2. Results for the orbit-dependent case are shown in Section 3.3.

3.1. The Canonical Case

3.1.1. The Flow Structure

When given enough time, all the “snapshot” simulations are able to reach steady states where the atmospheres reach their final mass and the accretion rates approach zero. Note that we do not take into account the contraction of the atmosphere occurring on the Kelvin–Helmholtz timescale, which is too long to be modeled in radiation-hydrodynamic simulations. Depending on the specific setup, the time required to reach the steady state varies. To avoid extensive computational time for some simulations to reach steady states, they are run only until they reach quasi-steady states. The time required for the system to reach a quasi-steady state is also the dynamical timescale. For the canonical case, the timescale is $\sim 6 \times 10^6$ s.

We then fit the temporal growth of the atmosphere mass with an asymptotic function to estimate the approximate final mass (see Appendix for a detailed description).

In Figure 3 we present the hydrodynamic solutions (gas density and temperature) of the canonical simulation in a quasi-steady state ($M_{\text{pl}} = 1.0 \, M_{\odot}$, $\rho_{\odot} = 10^{-9}$ g cm$^{-3}$, $v_{\odot} = 4.8$ km s$^{-1}$). Panels (a) and (b) show the 2D solutions while (c) and (d) show the 1D profiles along different angles.

A strong bow shock is formed in front of the planet with the shock front located at $3.6 \, R_{\text{pl}}$ (planet radii). The ram pressure from the nebular gas and the bow shock prevent a large amount of gas from being accreted to the planet on the side directly facing the shock front. But the planet still retains a proto-atmosphere from the post-shock gas that is largely hydrostatic in a steady/quasi-steady state. The proto-atmosphere is largely pressure-supported. The nebular gas is heated at the shock front due to strong compression and preheated beyond the shock front by the radiation emitted by the hot post-shock gas. This is a type of radiation shock called a supercritical shock (Sincell et al. 1999) and features a temperature spike at the density shock front (Figure 3(d)). The stronger the shock is, the higher the temperature spike can be and the larger the preheated region beyond the shock front is. Figure 3(d) also shows that the inner proto-atmosphere is mainly heated by the accretional energy, and the temperature of the outer layer (two to three planet radii) is mildly raised by the compression of the bow shock. There is

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Footnote 7: We define that the system reaches a quasi-steady state where the growth of the atmosphere mass becomes trivial—the time to grow another 0.1% of the total mass is much longer than the time to obtain the majority (90%) of the final mass.
also a small high-temperature region behind the planet caused by the converging flows from vortices. We illustrate the gas flow with the linear integral convolution (LIC) (Figure 3(a)) and streamlines (Figure 3(b)). Both illustrations show a clear boundary between two types of flow—gas entering the bow shock with larger impact parameter and flowing directly past the planet, and gas with relatively small impact parameter flowing back toward the planet in the downstream region, forming multiple stable vortices (“egg-shape” region, enclosed by the yellow dashed line in Figure 3(a)).

The “egg-shape” flow region resides in the post-shock subsonic area, with its boundary in front of the planet coinciding with the stagnation point of the bow shock. Interestingly, the proto-atmosphere is accreted not directly through the gas encountering the front of the planet, but through the gas flowing back toward the planet in the “egg-shape” pattern. Such patterns are clearly distinct from those of gas accretion on planets with circular orbits, where gas is accumulated from all directions (e.g., Ormel et al. 2015a, 2015b; Cimerman et al. 2017). The flow structure becomes stable soon after the bow shock is established.

As the simulation reaches a quasi-steady state, we dye the proto-atmosphere region with a tracer to track the gas movement over $\sim 5 \times 10^6$ s, a time long enough to see the gas replacement inside the “egg-shape” region (Figure 4). Although the tracer diffuses over time, it is clear that the majority of the dyed gas flows back to the planet inside the egg-shape region. A portion stays bound close to the planet, while the rest eventually flows out of vortices. These vortices then get replenished by the next batch of incoming gas. The gas inside the “egg-shape” region is constantly recycled and exchanges with the disk gas, with an estimated recycling timescale between $5 \times 10^5$ and $5 \times 10^6$ s, about half of the dynamical timescale.

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The Astrophysical Journal, 899:54 (18pp), 2020 August 10

Mai et al.

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8 The estimation of the timescale is based on whether the majority of the gas inside the “egg-shape” region is replaced. There is a range for this timescale because of the uncertainty caused by the diffusion of the tracer.
3.1.2. Definitions of the Atmosphere

Defining the boundary of the proto-atmosphere of an eccentric planet is far less straightforward than in the cases where planets are on circular orbits. The commonly used definitions for symmetric atmospheres such as the Hill radius and Bondi radius are no longer applicable in the supersonic environment. Like those around planets on circular orbits, the proto-atmosphere is always connected to and actively interacting with the disk gas (Section 3.1.1).

For the purpose of calculating the atmosphere mass, we provide three different ways to define a boundary for the proto-atmosphere based on the flow structures resolved by the hydrodynamic simulation:

1. A gas density contour around the planet that encloses the hydrostatic atmosphere and is not too distorted in shape because of the bow shock. We found that the $10^{-8.5} \, \text{g cm}^{-3}$ contour is most suitable when the background gas density is $\rho_i = 10^{-9} \, \text{g cm}^{-3}$. The mass enclosed by this boundary is $1.40 \times 10^{21} \, \text{g}$.
2. The boundary of the “egg-shape” region where the gas recycles in and out. There is $1.43 \times 10^{21} \, \text{g}$ of gas in this region when the system reaches a steady/quasi-steady state.
3. The boundary of the gas that stays gravitationally bound to the planet, according to Figure 4. The mass of this part of the gas is about $4.31 \times 10^{20} \, \text{g}$.

Figure 5 demonstrates the different boundaries of the atmosphere given by these definitions with dashed lines in different colors. As we will see in Section 3.2, the gas enclosed by the $10^{-8.5} \, \text{g cm}^{-3}$ contour line and the gas in the “egg-shape” region are of similar mass, both about half an order of magnitude higher than the bound mass. By subtracting the bound mass from the mass in the “egg-shape” region, we find the amount of recycling gas behind the planet to be $9.98 \times 10^{20} \, \text{g}$.

We would like to point out that the atmospheric pressure on the planet surface is probably a better metric of how much gas is retained, because in the current context the calculated atmosphere mass is relatively subjective—it depends on which boundary is used. In comparison, the surface pressure does not rely on a specific definition. The larger the surface pressure, the
thicker the atmosphere. In cases where the planet surface is partially or completely molten, the surface pressure directly determines how much volatiles can be dissolved in the magma ocean (e.g., Wu et al. 2018; Sharp & Olson 2019). The average surface pressure for the canonical case is $4 \times 10^{-2}$ bar. We use both surface pressure and the atmosphere mass to measure the amount of proto-atmosphere throughout the study.

3.2. Study of Sensitivity to Parameters

Does the proto-atmosphere of an eccentric planet always have a similar flow structure to that seen in the canonical simulation? How does it change in response to different planet–disk environments? To answer these questions, we vary the three input parameters—the relative velocity between the planet and the gas ($v_{\text{rel}}$), the planet mass ($M_{\oplus}$), and the background gas density ($\rho_{\text{bg}}$)—separately and carry out the corresponding “snapshot” simulations (see Table 1).

3.2.1. The Effect of Relative Velocity

The relative velocity between the planet and the disk gas directly determines the strength of the bow shock around the planet when it exceeds the sound speed ($\sim 1.2 \text{ km s}^{-1}$ for the assumed background disk gas). In the parameter study, we vary the relative velocity between 3.2 and 7.5 km s$^{-1}$, corresponding to planets with orbital eccentricities between 0.1 and 0.5.

The hydrodynamic solutions of these simulations reveal that the flow structures around the planet are similar to those in the canonical case. The “egg-shape” region forms behind the planet with part of the gas bound to the planet and the rest exchanging with the disk, regardless of how fast the planet is traveling through the gas (Figure 6). As the relative velocity gets larger, the opening angle of the bow shock becomes narrower. The larger ram pressure coming from the nebular gas suppresses the accretion of the atmosphere further and reduces the stand-off distance of the shock front. As a result, the planet keeps a smaller atmosphere with an even smaller portion of the bound part. Figure 7 shows how the atmosphere mass and planet surface pressure change with the variation of the relative velocity. The atmospheric properties show most dramatic changes when the planet is traveling relatively slowly in the disk gas (but is still supersonic). In the cases of high relative velocity, the “egg-shape” region is dominated by the recycling movements of gas.

3.2.2. The Effect of Planet Mass

The planet mass directly affects the amount of atmosphere that can be gravitationally accreted onto the planet. We vary the planet mass from 0.1 to $3 M_{\oplus}$, covering a range of terrestrial planets from the sub-Earth to super-Earth regime (Table 1). We assume that all simulated planets have Earth-like composition and interior structures (e.g., similar element ratios and temperature structures). Therefore, we calculate the planet radius as a function of planet mass using the ExoPlex mass–radius software package (Unterborn et al. 2018) for planets $\leq 0.7 M_{\oplus}$ and the mass–radius relationship described in Dressing et al. (2015) for planets $>0.7 M_{\oplus}$.

Figure 8 shows the hydrodynamic solutions for planets with 0.1, 0.7, and $2.0 M_{\oplus}$. We find that except for the case where $M_{\text{pl}} = 0.1 M_{\oplus}$ (e.g., the case of Mars), all other simulated systems maintain similar flow structures—a stable atmosphere with an “egg-shape” region. In the given context, a Mars-sized planet or planetary embryo is not able to hold a regular proto-atmosphere with the little gravity it provides. As can be seen from the leftmost panel in Figure 8, the supersonic gas forms a “secondary shock front” on the planet surface. The planet’s gravity is not high enough to focus the incoming gas, i.e., no bow shock is formed, and hence the incoming gas is able to directly strike onto the planet’s surface where it is shocked. The yellow dashed lines in the figure mark where the gas velocity reduces below sound speed. A planetary embryo with such a small size cannot hold a bound atmosphere. Recycling vortices are still present behind the planet, though this region can no longer enclose the whole planet. Note that the situation can change with different background setups, e.g., reducing the relative velocity between the planet and the disk gas could help a small planet object such as Mars to retain a normal atmosphere. If Mars was once scattered on an eccentric orbit (Hansen 2009), it is likely to experience dramatic atmosphere stripping and re-accretion repeatedly throughout the orbit. This can result in the loss of any outgassed atmosphere, which is replaced by the reducing H$_2$/He atmosphere.

On the other hand, more massive planets are able to greatly slow down the supersonic gas and hold atmospheres of a larger mass. The “egg-shape” regions around these planets also reveal more complicated vortices and other flow structures.

Figure 9 summarizes the trends of atmosphere mass and averaged planet surface pressure with increasing planet mass, similar to Figure 7. Both properties increase as the planet gets smaller.
more massive, most dramatically in the sub-Earth mass range. In our setups, planets with sufficient orbital eccentricity do not possess a bound atmosphere when their mass is lower than 0.5 \( M_\oplus \). The hydrodynamics around planets with mass <0.7 \( M_\oplus \) are dominated by the recycling gas flows.

### 3.2.3. The Effect of Background Gas Density

The background gas density can have values different from \( 10^{-9} \) g cm\(^{-3} \) for a number of reasons. As was mentioned in Section 2.2.2, different models for the solar/stellar nebula would provide augmented nebular density profiles (0.5−1.5 orders of magnitude higher). Besides the uncertainties from theoretical models, the age of the protoplanetary disk can also affect the nebular density in the background. Within 1−10 Myr, the nebular gas density can be lowered by one to two orders of magnitude as the disk evolves through accretion, wind, and photoevaporation (e.g., Mordasini et al. 2012; Bai 2016; Nakatani et al. 2018a, 2018b).

Unlike the relative velocity and the planet mass, the impact of the nebular gas density on our simulation solutions seems less straightforward. In our study, we perform the simulations with the background gas density varying from \( 10^{-7} \) to \( 10^{-10} \) g cm\(^{-3} \) while keeping other parameters the same. The resulting flow patterns and atmospheric properties do not change monotonically with the nebular density. When we lower the background gas density, the hydrodynamic solution presents the same flow pattern—the “egg-shape” recycling region (the right panel of Figure 10). However, the region expands and the planet is able to hold a more massive atmosphere. The decrease of the nebular density leads to a lower gas pressure in the background. With less ram pressure pushing against the moving planet, the bow shock becomes weaker and facilitates gas accretion onto the planet. In practice, we decrease the background gas density to as low as \( 10^{-11} \) g cm\(^{-3} \), in which case the planet retains an even larger atmosphere. However, we exclude the results from this simulation because it converges too slowly and it becomes too expensive computationally to reach a quasi-steady state.

When we elevate the background density, the hydrodynamics of the system seem to switch to a different regime. The solutions present a different flow structure (the left and middle panels in Figure 10). We no longer observe the stable recycling of gas through the “egg-shape” region. Instead, small-scale vortices constantly emerge and disintegrate behind the planet. In the case of \( 10^{-8} \) g cm\(^{-3} \) (DEN−8), we observe the presence of Kelvin–Helmholtz instability along the direction parallel to the shearing flow. The instability invokes propagating density waves, which are most prominent at two to eight planet radii behind the planet and weakened further downstream. In the case of \( 10^{-7} \) g cm\(^{-3} \) (DEN−7), some portion of gas appears to be flowing back to the planet near the symmetry axis. The formation of large vortices to initiate the recycling is unstable, however—different scales of vortices are frequently shredded and re-emerge. In both cases, no nebular gas is being stably recycled but a portion of atmosphere stays bound to the planet. Nonetheless, we can still define an atmosphere using a suitable density contour for each case. As the simulation converges, the atmosphere mass fluctuates around some constant value. By averaging these fluctuating values we have an estimate of the amount of atmosphere around the planet.

The fact that the hydrodynamics change with the background density is an effect of radiative transfer. Because the equations of hydrodynamics do not set any absolute scale of density, the solutions of simulations without radiative transfer should be self-similar, with the background density being a scaling factor. A typical optical depth for the proto-atmosphere within the bow shock is \( \sim 200 \) when the background density is \( 10^{-9} \) g cm\(^{-3} \). This quantity reaches \( \sim 600 \) when the background density is \( 10^{-10} \) g cm\(^{-3} \) and drops to \( \sim 20–30 \) when the background density is \( 10^{-8} \) or \( 10^{-7} \) g cm\(^{-3} \). The drastic drops in opacity and optical depths of atmospheres in the cases of high background density are caused by the evaporation of dust—the gas temperatures near the planet surface exceed 1500 K. This leads to a different hydrodynamics regime to the recycling regime in the cases of lower background density.

Figure 11 summarizes how the atmosphere mass and surface density change with the background gas density. We observe two hydrodynamics regimes operating in cases of different background density, which are likely invoked by the opacity jump in the atmospheres. In either regime, there are two competing mechanisms that affect how much atmospheres the planet can hold. In the regime where instabilities are present and the large-scale gas recycling is absent (DEN−7 and DEN−8), the atmosphere is more massive because of the sufficient gas supply from a dense nebular environment. This factor wins over the stripping effects from a larger ram pressure against the bow shock. The atmosphere is thin and compact. In the recycling regime, however, the drop in background gas density does not significantly limit the availability of nebular gas for accretion, but rather facilitates gas accretion by weakening the ram pressure. The atmosphere is thick and puffy. We conclude that the recycling regime is favorable for planets to keep a stable atmosphere in the planetary bow shock.

Lastly, we would like to point out that the parameter study in background gas density also provides qualitative estimates for the cases where planets are located at different distances from

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the star. If a planet is on an orbit further away from the star (e.g., 10 au), the decrease in the surrounding gas temperature and density can result in a reduction in the ram pressure against the planetary bow shock. The flow structure of the proto-atmosphere likely resembles that of the low-density case study, where the planet retains a puffy and massive atmosphere in the recycling regime. On the other hand, a planet located closer to the star (e.g., 0.1 au) is exposed to a denser and hotter nebular environment. With the surrounding temperature approaching 1000 K and the nebular density raised by 2 orders of magnitude, the proto-atmosphere likely presents instabilities as in those high-density case studies.

### 3.3. Orbit-dependent Simulation Results

In the second part of our hydrodynamic simulations, we focus on tracking the evolution of the proto-atmosphere as the planet moves on an eccentric orbit. All parameters relevant to the planet–disk environment are time-dependent, including the background gas density, the temperature, and the relative velocity between the planet and the gas (only the speed is time-dependent, the direction of velocity is assumed to be fixed given that the change of bow shock orientation is negligible in local-framed simulations—Figure 2). Therefore, the outcomes of the simulation are solely controlled by the orbital parameters (the semimajor axis and the eccentricity) as well as the planet mass.

We model a planet of 1 $M_\oplus$ traveling on an orbit with semimajor axis $a = 1$ au and eccentricity $e = 0.2$. The simulation starts with the planet at its perihelion. Figure 12 presents the periodic features reflected in the atmospheric properties as the planet completes 1.9 orbits. At small phase angles ($<\pi/3$), the planet undergoes a fast-accretion stage, trying to reach an equilibrium with the surrounding nebula. To ensure that the fluctuations of all calculated quantities are caused merely by orbital effects, we exclude the first half of an orbital period. From the first aphelion to the second aphelion (phase angle $= \pi - 3\pi$, shaded by light gray in Figure 12), the planet completes a full orbit.

We can see that the relative velocity between the planet and the gas rises from a minimum as the planet leaves its aphelion. However, the atmospheric properties—the surface pressure, temperature, the mass, and the mass accretion/loss rate—do not respond to the change immediately. The proto-atmosphere should have been undergoing stripping with the increasing relative velocity/Mach number, but the surface pressure, temperature, and mass continue to grow for a while before decreasing. On the other hand, the atmosphere is still experiencing mass loss even when the relative velocity starts to decline after reaching a peak (phase angle $= 3\pi/4$). To sum up, the system shows a delay in response to the time-dependent boundary conditions. The oscillations in atmospheric properties show a phase shift of $\sim \pi/4$, corresponding to an average reaction time $^{10} \sim 7 \times 10^5$ s, which matches the dynamical timescale of the system.

Note that in the orbit-dependent simulation, the relative velocity is not the only parameter affecting how much of the atmosphere can be retained. The time-dependent background gas temperature, density, and pressure can also make a difference, although their variations within one orbit are much smaller than those of the relative velocity. For example, the relative velocity/Mach numbers are similarly small for the planet at aphelion and perihelion. But the planet seems to retain more atmosphere after it passes aphelion, because the denser and hotter disk environment at perihelion leads to a larger ram pressure toward the planet, making the gas accretion less

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$^{10}$ We obtain the lag time by comparing the locations of peaks and valleys of the curves of the surface pressure and the relative velocity (Figure 12).
Kelvin–Helmholtz instability is observed in the case of $10^{-7}$ g cm$^{-3}$, forming density waves parallel to the symmetry axis. No gas is being steadily recycled but some atmosphere stays bound to the planet in both cases with the elevated background density.

![Figure 10](image1.png)

**Figure 10.** Gas density and the flow structure around the planet with various background nebular gas densities ($10^{-7}$, $10^{-8}$, and $10^{-10}$ g cm$^{-3}$, left to right), illustrated with LIC and streamlines. Note that the color scales in each panel are different from each other. The solutions from the cases of $10^{-7}$ and $10^{-8}$ g cm$^{-3}$ show a different flow structure than the regular “egg-shape” pattern. Vortices behind the planet are unstable—they constantly develop, get shredded, and disintegrate. In particular, Kelvin–Helmholtz instability is observed in the case of $10^{-8}$ g cm$^{-3}$, forming density waves parallel to the symmetry axis. No gas is being steadily recycled but some atmosphere stays bound to the planet in both cases with the elevated background density.

![Figure 11](image2.png)

**Figure 11.** Similar to Figures 7 and 9. The impact of the background gas density ($\rho_\text{bg}$) on the atmosphere mass and averaged planet surface pressure. Both increase with a smaller nebular density due to the lack of ram pressure. The gray dashed arrows indicate the trends as the density gets further reduced. The quantities also increase with a larger nebular gas density as the hydrodynamics switch to a different regime. See the text for details.

effective. We also notice that the changes in the surface temperature with phase are not entirely synchronized with the other properties—it drops much faster than it rises. Spontaneously, one could expect the surface temperature to change in phase with the change of surface pressure for a pressure-supported atmosphere. But when the surface pressure is high, the surface temperature can reach 1500–1600 K and drastically lower the local opacity (dust is evaporated). So as the atmosphere gets stripped (at high relative velocity/Mach number) it undergoes fast radiative cooling. However, the high relative velocity also produces a strong bow shock that dramatically heats up the compressed gas at the shock front.

The heat can be transferred to the atmosphere from outside to inside, creating a temporary temperature inversion. Eventually, the heat from shock gas prevents the surface temperature from further decrease and causes it to rise again (Figure 13).

The orbit-averaged values of different quantities—drawn as horizontal solid lines in Figure 12—are consistent with the results acquired from the “snapshot” simulation VEL4.2 (horizontal dotted–dashed lines). With the appropriate selection of input parameters, the “snapshot” simulation is also able to represent the “averaged” picture of the dynamic proto-atmosphere over the corresponding orbit.

4. Discussions

4.1. Comparison with Planets on Circular Orbits

The proto-atmosphere on low-mass planets with circular orbits has been studied in detail to explore the formation of super-Earths and Earth-like planets (see literature review in Section 1). By comparing our results with the outcomes from hydrodynamic simulations for planets on circular orbits, we identify a few major differences in atmosphere accretion on planets with the two types of orbits.

(1) The flow structure. The relative motion between the planet and gas is subsonic in cases where planets are on circular orbits. The gas accretion does not generate a bow shock. In 1D hydrodynamic simulations (e.g., Stökl et al. 2015, 2016), proto-atmosphere accretion on the planet is assumed to be in azimuthal symmetry—the infall of the nebular gas lies in the radial direction. In 2D and 3D simulations (e.g., Fung et al. 2015; Ormel et al. 2015a, 2015b; Cimerman et al. 2017; Kuwahara et al. 2019), the planet is considered to be embedded in a Keplerian disk. A local shearing flow with its reference frame is comoving with the planet as the gas travels faster on the side facing the star and slower on the other side. Both 2D and 3D simulations find a pressure-supported rotating atmosphere around the planet. In 2D, the atmosphere becomes isolated from the disk gas when the system reaches a steady state. In 3D, the atmosphere stays connected to the disk as the atmosphere is constantly exchanging gas with the nebula. The incoming gas enters the Bondi sphere around the planet at high latitudes and leaves at the equatorial regions. In all simulations, two horseshoe flow regions are seen on the front and rear sides of the planet. The situation of a planet experiencing a headwind from the disk gas in sub-Keplerian motion has also been considered. In such cases, the flow pattern becomes asymmetric...
around the planet as the streamlines are compressed toward the headwind. The nebular gas enters from the equatorial region and leaves at high latitudes. For figures of the detailed flow patterns of the above simulations, please refer to Fung et al. (2015), Ormel et al. (2015a, 2015b), Cimerman et al. (2017), and Kuwahara et al. (2019). In summary, proto-atmospheres on planets with both circular (subsonic) and eccentric (supersonic) orbits are actively interacting with the nebular gas through large-scale recycling. The recycling/replenishment timescale in the case of a circular orbit is generally longer (>10^7 s) than that of a typical eccentric planet simulated in this study (5 × 10^5–5 × 10^6 s).

(2) The steady state. In 2D simulations for planets on circular orbits, the gas accretion seems to be able to reach a steady state...
where the solutions no longer fluctuate. The flow pattern and other physical quantities (e.g., density, velocity), however, could be time-variable in some 3D simulations (Cimerman et al. 2017). But some other simulations suggest that they can reach steady states (T. Moldenhauer et al. 2020, in preparation). In comparison, gas accretion onto planets with eccentric orbits can also reach steady/quasi-steady states as shown in this study.

(3) Atmospheric properties. Planets on circular orbits are able to hold much more massive atmospheres. The 1D models in Stökl et al. (2015, 2016) point out that a 1 $M_\oplus$ planet can accrete up to 300 bar (or $10^{25}$ g) of atmosphere, which is $\sim$0.2% of the planet mass. The 2D simulations in Ormel et al. (2015a) and 3D models (T. Moldenhauer et al. 2020, in preparation) give similar or slightly lower values. In terms of

Figure 13. The evolution of gas temperature over one full orbit (phase angle $\pi$–3$\pi$, matching the gray shaded region in Figure 12). As the relative velocity between the planet and the gas increases, the bow shock reheats the proto-atmosphere from outside to inside, stopping the radiative cooling.
surface temperature, a 1 $M_⊕$ planet on a circular orbit can be $\geq 3000$ K (T. Moldenhauer et al., 2020, in preparation; Stökl et al., 2016), whereas for an eccentric orbit we find 1000–2000 K. This is due to the accretion of a much smaller atmosphere and implies that dust grains dominate the opacity in such an atmosphere.

A summary of the above comparison is presented in Table 2.

4.2. Comparison with the Bondi–Hoyle–Lyttleton (BHL) Accretion

The accretion on a gravitating object traveling supersonically in a homogeneous medium is a classical problem called the BHL accretion (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944). For decades, numerous analytical and numerical studies have been exploring the flow structure and the stability of BHL accretion (see Edgar 2004; Foglizzo et al. 2005 for reviews). Typical applications for these BHL accretion models include wind accretion in binary systems (e.g., Taam et al. 1991; Xu & Stone 2019), accretion on other compact objects such as black holes (e.g., Pogorelov et al. 2000), and the protostellar clusters and galaxy clusters (e.g., Sakelliou 2000; Bonnell et al. 2001).

Gas accretion on an eccentric planet is also a BHL accretion problem in principle, although the complications from radiative properties and boundary conditions can deviate the solutions from the classical derivatives. In fact, the flow structure and stability of BHL accretion are proven to depend strongly on the chosen grid method (2D planar, 2D axisymmetric, or 3D), the given parameters, and the accretor’s properties (Foglizzo et al. 2005). Our results in this study are aligned with the previous finding that simulations in a 2D axisymmetric case are in general stable (e.g., Pogorelov et al. 2000; Foglizzo et al. 2005). The “egg-shape” flow pattern—where a portion of the gas flows back to the planet in the post-shock region—is also commonly observed in other axisymmetric simulations (e.g., Koide et al. 1991; Pogorelov et al. 2000; MacLeod & Ramirez-Ruiz 2015).

4.3. The Damping of Orbital Eccentricity

Though planets and planetary embryos can be scattered and/or migrate in the young protoplanetary disk, their phases on eccentric orbits are believed to be temporary as long as the disk gas is present. Planets traveling in a gaseous disk can experience both aerodynamic and gravitational gas drag. The aerodynamic drag is the pressure resistance that any gas or fluid exerts on the object moving inside it, and it is more effective for smaller bodies such as planetesimals (e.g., Kominami & Ida 2002). The gravitational drag arises from torques as the planet interacts with the gaseous disk (e.g., Papaloizou & Larwood 2000). It is more prominent in massive objects such as planetary embryos and planets.

The aerodynamic damping timescale can be calculated from the formulae in Tanaka & Ida (1999) and Kominami & Ida (2002) as

$$\tau_{\text{aero}} \approx \frac{M_{\text{pl}}}{\pi R_{\text{pl}}^2 \rho_{\infty} v_{\text{pl}}} \approx 3 \times 10^5 \left(\frac{e}{0.2}\right)^{-1} \left(\frac{M_{\text{pl}}}{M_⊕}\right)^{1/3}$$

$$\times \left(\frac{\rho_{\infty}}{10^{-9} \text{ g cm}^{-3}}\right)^{-1} \left(\frac{r}{1 \text{ au}}\right)^{1/2} \text{ yr},$$

where we approximate the relative velocity between the planet and gas $v_{\text{pl}}$ as $(1/2)e v_K$, and $v_K = \left(G M_\odot/r\right)^{1/2}$ is the Keplerian speed.

For low eccentricities (e.g., $e \leq H/r$ or $v_{\text{pl}} \leq c_\infty$), the damping timescale for the gravitational drag is given as

$$\tau_{\text{grav,le}} \approx \left(\frac{M_\odot}{M_{\text{pl}}}\right) \left(\frac{M_\odot}{\Sigma_r r^2}\right)^4 \left(\frac{c_\infty}{v_K}\right)^4 \frac{\Omega_K}{\rho_{\infty}}$$

$$\approx 5 \times 10^2 \left(\frac{M_{\text{pl}}}{M_⊕}\right)^{-1} \left(\frac{\rho_{\infty}}{10^{-9} \text{ g cm}^{-3}}\right)^{-1} \times \left(\frac{r}{1 \text{ au}}\right)^{-3/4} \text{ yr.}$$

$\Sigma_r = \rho_{\infty} H \sqrt{2\pi}$ is the surface density of the disk gas. $\Omega_K = \left(\frac{GM_\odot}{r^3}\right)^{1/2}$ is the Keplerian frequency (Kominami & Ida 2002).

However, Papaloizou & Larwood (2000) found that when $e > 1.1 H/r$, the sign of the torque on the planet reverses and leads to an eccentricity damping timescale strongly dependent on $e$. The ratio of the disk scale height to its radius, $H/r$, ranges from 0.02 to 0.07 throughout the protoplanetary disk (0.1–10 au). For planets in the supersonic regime as we consider in this study ($e \geq 0.1$), we need to calculate a damping timescale different from Equation (11). For such cases, the authors suggest to replace $\tau_{\text{grav,le}}$ by $[e/(H/r)^3]^{1/2} \tau_{\text{grav,le}}$. So we have

$$\tau_{\text{grav,le}} \approx 1 \times 10^4 \left(\frac{e}{0.2}\right)^{3} \left(\frac{M_{\text{pl}}}{M_⊕}\right)^{-1} \left(\frac{\rho_{\infty}}{10^{-9} \text{ g cm}^{-3}}\right)^{-1} \times \left(\frac{r}{1 \text{ au}}\right)^{-3/2} \text{ yr.}$$

The ratios of the these timescales are

$$\frac{\tau_{\text{aero}}}{\tau_{\text{grav,le}}} \approx 600 \times \left(\frac{e}{0.2}\right)^{-1} \left(\frac{M_{\text{pl}}}{M_⊕}\right)^{4/3} \left(\frac{r}{1 \text{ au}}\right)^{3/4}$$

$$\frac{\tau_{\text{aero}}}{\tau_{\text{grav,le}}} \approx 3 \times \left(\frac{e}{0.2}\right)^{-4} \left(\frac{M_{\text{pl}}}{M_⊕}\right)^{-1/3} \left(\frac{r}{1 \text{ au}}\right)^{2}.$$

Therefore, for planets more massive than $10^{25}$ g on orbits with low eccentricities, the orbits are mainly circularized by the gravitational drag (Kominami & Ida 2002). For planets on orbits with higher eccentricities, aerodynamic gas drag
dominates if $M_{\text{pl}} < 0.1 M_{\text{pl, 15damp}}$, while gravitational drag dominates if $M_{\text{pl}} > 1 M_{\text{pl, 15damp}}$. These calculations are consistent with calculations of eccentricity damping by Morris et al. (2012).

The orbital eccentricity can also be damped by the dynamical friction coming from the swarms of planetesimals scattered throughout the disk. The damping timescale has a similar expression to Equation (11), except that $\Sigma_{\text{e}}$ is substituted by the surface density of solids in the disk $\Sigma_{\text{solid}}$ and $e_{\text{c}}$ is substituted by the velocity dispersion of planetesimals $v_{\text{dis}}$. Therefore, the mechanism can either be incorporated into the gravitational drag regime (Kominami & Ida 2002) or neglected in cases where $e > 0.03$ because the gravitational drag dominates over dynamical friction (Morris et al. 2012).

The damping of orbital eccentricity follows
\[
\frac{de}{dt} = -e \tau_{\text{damp}}^{-1}
\]
(15)
where $\tau_{\text{damp}}$ is the damping timescale. If it is substituted by $\tau_{\text{grav, he}}$, $\frac{de}{dt}$ becomes linearly proportional to $e^{-2}$ and $M_{\text{pl}}$. The lower the eccentricity (still larger than 0.1) and the larger the planet mass, the faster its orbit gets damped.

For a typical planet simulated in our models, its eccentric orbit is circularized in about 0.1 Myr, which is much longer than the relevant timescales in this study. The damping of eccentricity is therefore negligible in both “snapshot” and orbit-dependent simulations. The planets may be able to hold more atmospheres as their orbits get circularized if the ambient disk gas has not yet dissipated. But this procedure can be complicated, because the damping also vanishes with the disappearing disk gas.

4.4. Limitations of This Study

The study does not consider the cases where the relative velocity between the planet and the gas is below sound speed (e.g., orbital eccentricity is very small, $e < 0.08$). In such cases, the planet does not generate a bow shock that compresses and heats up the gas in front of the planet, and the stripping of the proto-atmosphere will be much less effective. In fact, it is no longer suitable to model planets in this regime with 2D axisymmetric simulations because the relative velocity ($v_{\text{rel}}$) could be comparable to the shear or headwind velocity of the ambient gas. To model gas accretion on planets traveling at subsonic speed, we suggest using the grid methods adopted for planets experiencing a headwind on circular orbits (Ormel et al. 2015a, 2015b, T. Moldenhauer et al. 2020, in preparation). The proto-atmosphere is predicted to be asymmetric and less massive than in the circular cases, but much more massive than in the supersonic cases. As our paper solely focuses on eccentric planets in the supersonic regime, the modeling of gas accretion on subsonic planets is left as future work. It will be interesting to compare the results from these models with the circular cases and the supersonic cases.

Another limitation of this study comes from the assumption of axisymmetry. A number of numerical simulations on BH accretion have adopted the full 3D grid method to represent the more realistic geometry. Unfortunately, most of them are not stable (Foglizzo et al. 2005). The 3D simulations usually break the axial symmetry of the flow structure and develop instabilities downstream of the bow shock (e.g., Ruffert & Arnett 1994). These instabilities are not as prominent and strong as the “flip-flop” behaviors observed in 2D planar simulations and could arise from numerical artifacts. Nonetheless, the gas is still observed to be flowing back toward the accretor in the post-shock region, similar to the 2D axisymmetric simulations. We expect that the hydrodynamic solutions for the atmospheres (e.g., density, pressure, temperature, mass) will be within the same orders of magnitude as obtained in this study, regardless of the adopted grid methods.

Lastly, we would like to point out that we neglect solid accretion that could occur at the same time as gas accretion. We assume that the planet never grows in mass and the planet luminosity is barely affected by pebble/planetesimal accretion. Solid accretion is common and important for planet formation in young disks ($\leq 5$ Myr), and luminosity feedback could be important (Mordasini 2013). There are several studies that have considered the impacts of orbital eccentricity on solid accretion (e.g., Lissauer et al. 1997; Liu & Ormel 2018). Given that the timescales relevant to gas accretion in this study are days to weeks, the neglect of long-term effects from solid accretion can be justified.

5. Summary

Planet migration and scattering are common in young planetary systems. Planets can be excited onto eccentric orbits and their atmospheres can undergo drastic stripping. In this study, we have performed hydrodynamic simulations to explore the presence of dynamic H2/He proto-atmospheres around low-mass planets with eccentric orbits. We have especially focused on planets that are traveling supersonically through the disk gas. In the “snapshot” simulations, we specify the disk–planet environment with the relative velocity between the planet and the gas, the planet mass, and the background gas density as input parameters. We analyze the corresponding flow structures and discuss how the atmospheric properties depend on the change of each parameter. In the orbit-dependent simulation, we allow the above parameters to be dependent on the time-varying location of the planet on an eccentric orbit to track the orbital evolution of the proto-atmosphere.

Our major findings and conclusions are summarized as follows.

1. The hydrodynamic simulations of gas accretion on supersonic planets are generally able to reach steady states. Gas entering the planetary bow shock with small impact parameters flows back toward the planet downstream of the shock, forming an “egg-shape” region with stable vortices. The proto-atmosphere is exchanging gas with the nebula via the large-scale recycling within this region, while a small portion of the gas can stay bound to the planet. The recycling timescale is estimated to be $10^7–10^{10}$ s depending on the actual disk–planet environment.

2. Planets on eccentric orbits are able to retain atmospheres despite the supersonic speeds relative to the nebular gas. But they possess much smaller proto-atmospheres than planets on circular orbits. For the investigated planets traveling at supersonic speeds, the stripping effect from the planetary bow shock is so strong that the atmospheric surface pressures are merely $10^{-2}–10^{-1}$ bar, about four orders of magnitude lower than those of planets on circular orbits. The range of the atmosphere mass is $10^{21}–10^{22}$ g ($10^{-5}–10^{-4}$% $M_{\odot}$), which is about three to four orders of magnitude smaller than that in the circular cases. Therefore, planet migration and/or scattering can be recognized as one of the important causes of atmosphere stripping and an efficient means of mass loss.

3. The larger the relative velocity between the planet and the gas is, the smaller the proto-atmosphere becomes. High
relative velocity/Mach number drives stronger planetary bow shocks that effectively strip the atmospheres.

4. The more massive the planet is, the larger the amount of atmosphere it can hold. Planets with a mass lower than $0.5 \, M_⊕$ cannot hold a bound atmosphere, but the situation can change with different background setups. If a planet with such low mass is ever on an eccentric orbit, it likely also loses any outgassed atmosphere and replaces that with a nebular atmosphere. Such a process has chemical consequences by exposing the planet to much more reducing gases ($H_2$ versus $CO_2$, $H_2O$).

5. The planet could retain more atmosphere when the background gas density is lower (e.g., $<10^{-9} \, g \, cm^{-3}$), because of the lower ram pressure coming from the nebula. Augmented gas density ($>10^{-9} \, g \, cm^{-3}$) could, however, introduce instabilities in the flow structure and switch the hydrodynamics to a different regime. In this regime where the recycling flow is no longer present, the planet can also keep more atmosphere because the dense nebula supplies sufficient gas for accretion.

6. The atmospheric properties (surface pressure, surface temperature, and mass) show oscillatory patterns as the planet moves on an eccentric orbit. The time-varying relative velocity between the planet and the gas is the main driver of the oscillations, but the changes in background gas density, temperature, and pressure also affect them. The oscillations show a delay in response to the time-dependent boundary conditions, with an average reaction time similar to the dynamical timescale of the system. The orbital “averaged” picture of the dynamic proto-atmosphere can be represented by the “snapshot” simulation.

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Appendix

Estimation of the Final Atmosphere Mass

In our performed simulations, the temporal growth of the proto-atmosphere is rapid at the beginning but the growth rate

Figure A1. The evolution of gas density and the flow structure at the early stage of the canonical simulation. The “egg-shape” pattern is formed and stabilized soon after the bow shock is established. Both the proto-atmosphere and the “egg-shape” region quickly expand in size over time (see the definitions of proto-atmospheres in Section 3.1.2).
For each simulation case that needs line-fitting, we provide an estimated atmosphere mass matching the ones in the simulation cases that quickly converge and is proven valid in the parameter study. See Section 3.1.2 for the definitions of a proto-atmosphere in detail.

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Mai et al.
