Genomic signatures of speciation in butterflies

Qian Cong[2,#], Jing Zhang[2], and Nick V. Grishin[1,2,*]

[1]Howard Hughes Medical Institute, University of Texas Southwestern Medical Center, 5323 Harry Hines Boulevard, Dallas, Texas 75390-9050, USA

[2]Departments of Biophysics and Biochemistry, University of Texas Southwestern Medical Center, 5323 Harry Hines Boulevard, Dallas, Texas 75390-8816, USA

[*]Contact: grishin@chop.swmed.edu

[#]Current address: Department of Biochemistry, University of Washington, Seattle, WA, 98105, USA

ABSTRACT

Studies of life rely on classifying organisms into species. Contrary to a frequent belief, simple and quantitative standards for species delineation are lacking, and debates about species delimitation create obstacles for conservation biology, agriculture, legislation, and education. To tackle this key biological question, we have chosen butterflies as model organisms. We sequenced and analyzed transcriptomes of 186 butterfly specimens representing pairs of close but clearly distinct species, conspecific populations, and taxa that are debated among experts. We find that species are robustly separated from conspecific populations by the combination of two measures computed on Z-linked genes: fixation index that detects hiatus between species, and the extent of gene flow that quantifies reproductive isolation. These criteria suggest that all 9 butterfly pairs that caused experts' disagreement are distinct species, not populations or subspecies. When applied to *Homo*, our criteria agree that all modern humans are the same species distinct from Neanderthals, suggesting relevance of this study beyond butterflies. Furthermore, we found that divergence and positive selection in proteins involved in interaction with DNA (including proteins encoded by *trans*-regulatory elements), circadian clock, pheromone sensing, development, and immune response recurrently correlate with speciation. A significant fraction of these divergent proteins is encoded by the Z chromosome, which appears to be more resistant to introgression than autosomes. Taken together, we find possible common speciation mechanisms in butterflies, present additional support for an important role of the Z chromosome in speciation of butterflies, and suggest quantitative criteria for butterfly species delimitation using genomic data, which is vital for the exploration of biodiversity.

KEY WORDS: reproductive barrier, classification, mating, sex chromosomes, suture zone, introgression

INTRODUCTION

"I was much struck how entirely vague and arbitrary is the distinction between species and varieties" wrote Darwin in his classic book "On the Origin of Species" (Darwin, 1859). While Darwin did not elaborate on the conceptual difference between varieties and species, Dobzhansky (Dobzhansky, 1935, 1937) and Mayr (Mayr, 1940, 1942, 1963) put forward the widely used biological species concept, in which species were separated from each other by reproductive isolation, while varieties, including populations and subspecies, were not. Partly due to the challenge in observing and quantifying reproductive isolation directly, other species concepts have been proposed to classify animals by morphological (Cronquist, 1978), and ecological (Leigh Van, 1976) differences between population, by phylogenic relationship (Cracraft, 1983), or by genotypic clustering (Mallet, 1995), among many others (Coyne and Orr, 2004).

Modern genetic studies of animals revealed profound gene flow (introgression) between distinct species, blurring the boundaries between species. This relatively new concept suggests that the reproductive barrier between species, especially sister species, is frequently incomplete (Fontaine et al., 2015; Heliconius Genome Consortium, 2012; Villanea and Schraiber, 2019). There is hardly a question as contentious in biology as the definition of species, conceptually and practically (Freudenstein et al., 2017). The perceived distinctness between animals recognized as different species, despite continuing gene flow between them (Mallet et al., 2016), dazzled many biologists. However, a practical criterion suggested by Sperling, i.e. "the genomic integrity species definition", may be applied to butterflies. In this definition, species are populations that are able to maintain their genomic integrity when contacting each other, despite some occasional mating and gene exchange. In addition, allopatric populations can be considered as species if their genomic divergence is at the level of sympatric sister species (Sperling, 2003).

Comparisons of the genomes of sister species reveal a widespread yet heterogeneous divergence (Ellegren et al., 2012; Harrison and Larson, 2014; Lawniczak et al., 2010; Michel et al., 2010) and differential introgression across different genomic loci (Rieseberg et al., 1999). These studies also show that sex chromosomes (Carneiro et al., 2010; Ellegren et al., 2012; Lawniczak et al., 2010) are restricted in gene flow, which is consistent with the two important observations regarding speciation: Haldane's rule (Haldane, 1922) and the "large X (or Z) effects" (Coyne, 1992b). The first rule states that the F1 hybrids of the heterogametic sex are more likely to be inviable or sterile than the homogametic sex, and the second describes the disproportionally larger effect of the X (or Z) chromosome than autosomes in causing hybrid sterility or inviability (Coyne, 2018). Both rules suggest the essential role of sex chromosomes in speciation and imply a higher barrier to transfer genes encoded on the sex chromosomes between species.

A number of genes involved in reproductive isolation between species have been identified in experimental studies, mostly in *Drosophila* (Barbash et al., 2003; Brideau et al., 2006; Maheshwari and Barbash, 2011; Phadnis et al., 2015; Presgraves et al., 2003; Tang and Presgraves, 2009; Ting et al., 1998). Analysis of these speciation genes suggest that they frequently show signatures of positive selection and several of them are related to transcriptional regulation (Tang and Presgraves, 2009). A lot more genes may contribute to the reproductive isolation between species pairs in nature. For example, the sterility of male hybrids between *Drosophila simulans* and *D. mauritiana* was estimated to be contributed by over 100 genes (Johnson and Kliman, 2002; Wu et al., 1996). With the advent of genomic sequencing, we are poised to advance the understanding of the molecular mechanisms of reproductive isolation in a broader spectrum of organisms, and to define species on the basis of their genotypes. Butterflies, as represented by *Heliconius*, have been used as model organisms to study how introgression shapes the evolution of phenotypes. Being well-studied morphologically, broadly distributed with many different species and diverse phenotypes, butterflies may be good models to study how species integrity is maintained despite the ongoing gene flow. In addition, criteria suggested by genomic data may resolve some debates about the taxonomic status of taxa as species vs. subspecies and populations.

Introduced by Remington (Remington, 1968), a suture zone is a limited geographic area that appears to be a common boundary between many narrowly sympatric and frequently very close pairs of species on either side of the suture zone. Most suture zones in North America lie in the western part of the continent and are associated with mountain ranges separating populations (Remington, 1968). More interesting and subtle zones are to the east. They lack obvious geographic barriers and offer challenges for finding the isolation mechanisms between species. Despite on-going debates about whether some of Remington's suture zones are real (Swenson and Howard, 2004), the Central Texas suture zone where western and eastern populations meet has been well-characterized in birds (Newton, 2003; Swenson and Howard, 2005). Over 20 pairs of bird species are known to be split into western and eastern forms with the boundary in Texas. Remington suggested that the central Texas suture zone was a "mature zone" because many western-eastern species pairs are well isolated reproductively and rarely hybridize when they meet in Texas (Rising, 1983). At least 25 pairs of butterfly species contact each other in Central Texas (Scott, 1986).

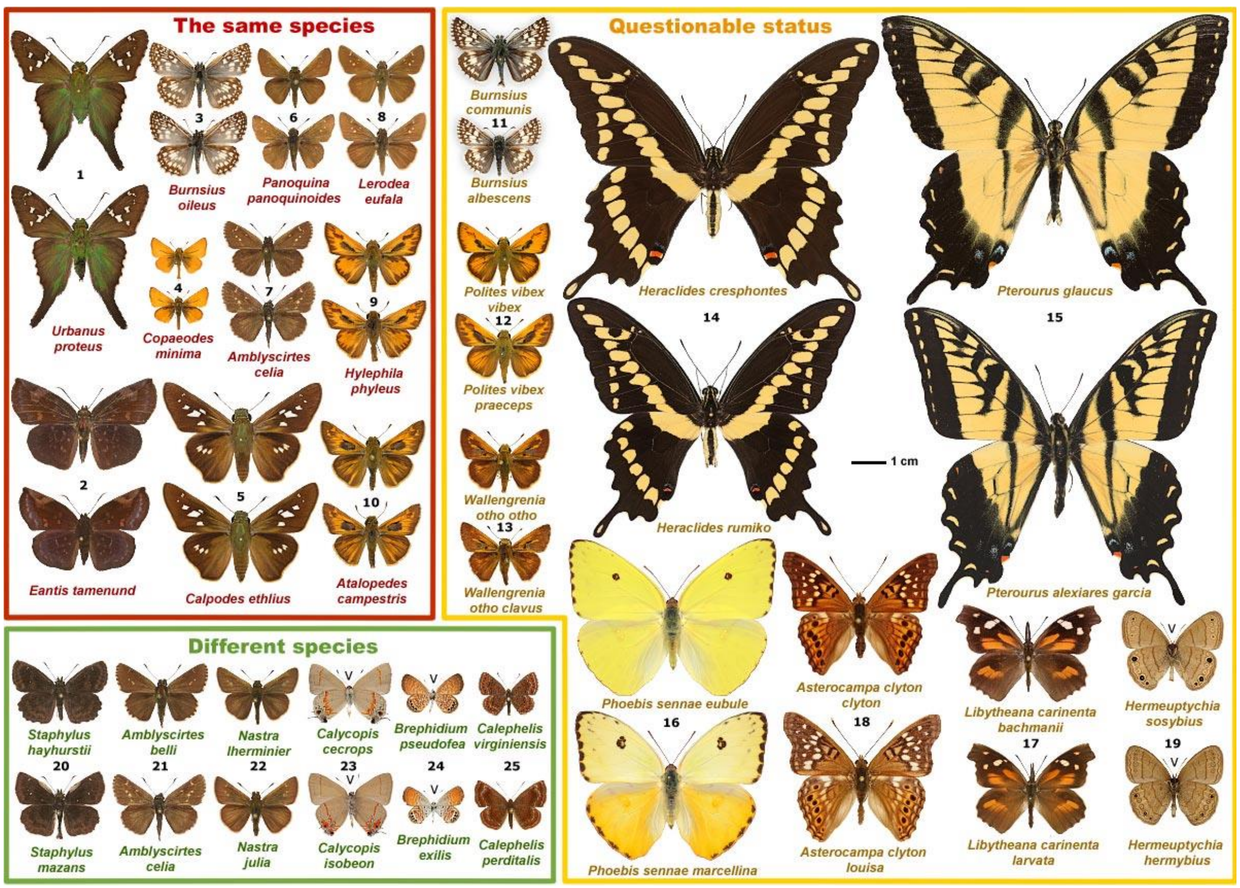

Fig. 1. Pairs of taxa around the central Texas suture zone analyzed in this study. Pairs in the red box are expected to be the same species (negative control); pairs in the green box are well-separated, different species (positive control); pairs in the yellow box include possible species or subspecies, but experts disagree on their status (test set). Specimens are shown in pairs of counterparts: eastern is above and western is below, and species names are given below specimens. Dorsal side of each specimen is shown except when marked with "V" between the antennae, which indicates that ventral surface is shown. Numbers shown between the specimens on each pair correspond to those used in Fig. 2.

Extensive characterization of butterflies across suture zones is still lacking. Casual observations reveal several known pairs of butterfly species segregated in western (more precisely, southwestern) and eastern (northeastern) forms around the central Texas suture zone. Several pairs have been studied at the genomic scale, for instance, *Calycopis cecrops* (eastern) and *C. isobeon* (western) (Cong et al., 2017; Cong et al., 2016a), *Phoebis sennae eubule* (eastern) and *P. sennae marcellina* (western) (Cong et al., 2016b), and *Heraclides cresphontes* (eastern) and *H. rumiko* (western) (Cong and Grishin, 2018). These studies revealed differences in the degree of genomic divergence and hint at some common mechanisms of speciation. To better understand the genomic signatures of speciation across the central Texas suture zone and to probe possible evolutionary scenarios of speciation, we gathered 25 pairs (Fig. 1) of butterflies distributed in both eastern and western sides of this suture zone and obtained their RNA-seq data (Table S1). The “eastern” populations correspond to taxa widely distributed over the eastern United States from Texas to Florida and northwards to Canada in many species. The eastern US zone is characterized by colder climate and higher humidity. The "western" populations include taxa that are distributed from central Texas southwards into Mexico and frequently westwards to variable extent, sometimes all the way to the Pacific coast. The southwestern zone is warmer and typically dryer, especially westwards.

The 25 pairs included (1) positive controls: well-differentiated species of unquestionable distinctness, such as *Nastra lherminier* (eastern) and *N. julia* (western) or *Staphylus hayhurstii* (eastern) and *S. mazans* (western); (2) pairs that may be different species, but opinions differ regarding their taxonomic status: some of these taxa are currently treated as subspecies, i.e., geographic races that differ morphologically but are not expected to show reproductive isolation strong enough to qualify as species, e.g., *Wallengrenia otho otho* (eastern), and *W. otho clavus* (western); and (3) negative controls: species that are known to be morphologically uniform across their distribution from east to west and are not expected to speciate across the suture zone, such as *Lerodea eufala* and *Hylephila phyleus*. Four out of six positive control pairs, including *Staphylus hayhurstii* and *S. mazans*, *Amblyscirtes belli* and *A. celia*, *Calycopis cecrops* and *C. isobeon*, *Brephidium pseudofea* and *B. exilis*, overlap in central TX for a range of over 200 miles, not as strays, but as residents, and therefore are sympatric species. These pairs have likely undergone speciation when they were allopatric populations separated in different areas, possibly during the ice ages. The fact that entomologists have consistent opinions about them being different species is partly due to their sympatry, together with their distinct morphology, especially in the shape of genitalia. Cases where experts disagree on their taxonomic ranks are mostly allopatric or parapatric, with the only exception being *Burnsius communis* and *B. albescens*.

The 25 gathered pairs represent the entire spectrum along the speciation continuum (Powell et al., 2013), from conspecific populations, through putative incipient species to well established species. Previous studies of species pairs representing the speciation continuum suggested that the probability of ongoing migration between species/population pairs determined using demographic models can clearly separate pairs of different species from conspecific populations with only a few (less than 10%) cases in the grey zone (Roux et al., 2016). We expect that delineating species boundaries using genomic data will become a common practice, calling for simpler indicators of species. By measuring the divergence between eastern and western populations, we aim at detecting general trends of speciation and isolation (or lack of them) in butterflies, revealing the possible molecular mechanisms for butterfly speciation across suture zones, and establishing some easy-to-compute measures to quantify genome-level isolation in the process of speciation.

RESULTS AND DISCUSSION

Genomic measures to quantify the reproductive barrier and define species

In practice, species can be defined by the hiatus (i.e. discontinuity) between them that results from at least partial reproductive barriers (Sperling, 2003). Historically, decisions about species boundaries were mostly based on morphology, and animals were partitioned into phenotypically distinct groups separated from each other by discontinuity in variation. Moving to genotypes, a standard measure of genomic distinctness is fixation index (F_{ST}). F_{ST} values computed over protein sequences encoded by transcripts that are present in at least 15 of 25 population pairs in our study are shown in the upper right corner of Fig. 2A (x-axis only). F_{ST} values calculated on DNA sequences gave very similar results. Although F_{ST} for positive controls (well-established different species) are always higher than the negative controls (conspecific population pairs), the values of F_{ST} over all proteins show a continuous distribution without a break between pairs of species and pairs of varieties. To quantify their reproductive isolation, we introduced the index of gene flow (I_{GF}) between each pair. We identify introgressed regions between populations using G_{min} (criterion: $G_{min} < 0.25$), which is defined as the ratio between the minimal hamming distance and the average hamming distance between sequences of different populations. An introgressed allele should reduce the minimal genetic distance between two populations much more than the average genetic distance, leading to low G_{min} values (Geneva et al., 2015). I_{GF} approximates the average fraction of introgressed segments from the other population in each specimen. This measure (y-axis in upper right corner of Fig. 2A) separates the positive from negative controls with a larger gap, but nevertheless forms a continuous spectrum for all analyzed pairs, similar to F_{ST}.

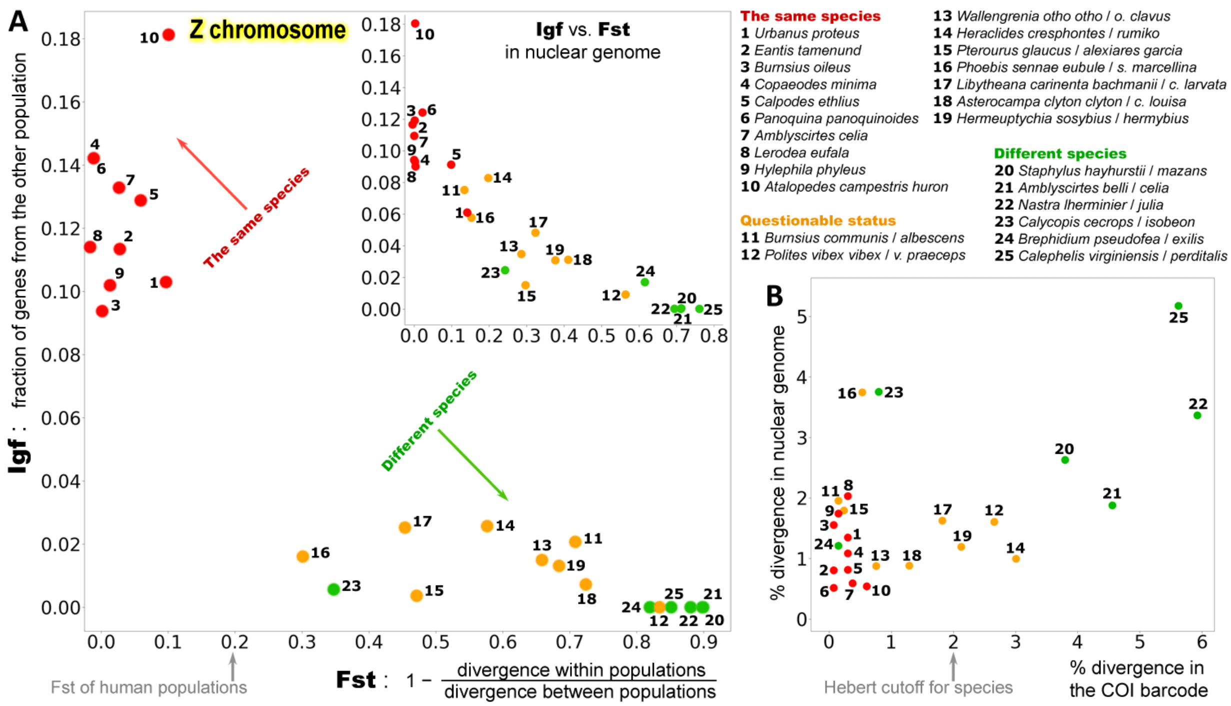

Fig. 2. Quantification of the reproductive barrier and genomic criteria for defining species. (A) Fixation index (F_{ST}) of Z-linked proteins and index of gene flow (I_{GF}) calculated on Z-linked genes clearly distinguish pairs of different species from conspecific pairs, while the same measurements computed on all nuclear genes present in RNA-seq (upper right corner) dataset do not separate them as well. (B) Divergence (percent of different nucleotides) in COI barcode and nuclear genes performs poorly in evaluating whether two taxa are different species.

We reason that the continuity in the distribution of F_{ST} may be caused by incidental hybridization, gene flow and introgression between species, all of which make different species more similar to each other. For example, introgression between *Heliconius* species plays an important role in phenotypic mimicry, with essential regions regulating wing pattern development being transferred between species (Heliconius Genome Consortium, 2012). We also documented introgression of mitochondria between a pair of well-established species used in this study: *Calycopis cecrops* and *C. isobeon* (Cong et al., 2017; Cong et al., 2016a). A lower level of introgression and higher relative divergence in the sex chromosome was reported in a range of species (Carneiro et al., 2010; Charlesworth et al., 1987; Ellegren et al., 2012; Lawniczak et al., 2010; Van Belleghem et al., 2018) and sex-linked genes were thus suggested to be good markers for speciation (Qvarnstrom and Bailey, 2009; Sperling, 2003). We tested whether restricting the analysis to Z-linked proteins would lead to a better separation between the positive and negative controls.

Remarkably, the same measures (F_{ST} and I_{GF}) calculated on Z-linked genes reveal a prominent break in the continuity of the distribution (Fig. 1A). F_{ST} and I_{GF} together definitively partition all 25 pairs into two groups. Negative controls are characterized with $F_{ST} < 0.10$ and $I_{GF} > 0.09$. All others (15 pairs, all positive controls and putative species pairs) form another group with $F_{ST} > 0.30$ and $I_{GF} < 0.025$. The natural break in both F_{ST} and I_{GF} suggests all of the putative species behave similarly to the positive controls, and thus it is reasonable to treat them as distinct species.

According to the biological species concept, species differ from varieties by the existence of a reproductive barrier. Although this barrier is incomplete for some genomic loci, identifying the loci that resist to gene flow and maintain genetic integrity helped us to observe the break in genetic divergence caused by the reproductive barrier. Haldane's rule (Haldane, 1922) and the "large X (or Z) effects" has been seen in a wide range of species using either ZW or XY sex determination (Coyne, 2018). These rules imply that Z or W chromosomes should be more resistant to introgression than autosomes. Therefore, the superior performance of Z chromosome in species delineation we observed in butterflies, may be generally true in a wide range of species including other insects, birds and mammals. However, exceptions to such trends may exist, for example, in cases of hybrid species. A hybrid species may inherit nearly the entire Z chromosome from one parent species, making them inseparable using our criteria. Autosomal genes inherited from another parent could be sufficient to establish the reproductive barrier between the hybrid and the parental species that contributed most of its Z chromosome to the hybrid species.

The combination of the two criteria we found here, $F_{ST} > 0.30$ and $I_{GF} < 0.025$, when computed on a large set of Z-linked genes, may be used to indicate pairs of different butterfly species. Both of these measures can be computed based on the genomic or RNA-seq data for minimally two specimens from each population. When there are more than 2 specimens, we computed these values by randomly sampling two specimens from each population for each gene, thus these values are not biased by sample size. Studies of human populations show that maximal F_{ST} between human populations is about 0.2 (Nelis et al., 2009) and humans have about 1.5–2.1% genes introgressed from Neanderthals (Wall and Yoshihara Caldeira Brandt, 2016). Therefore, our criteria for species boundaries are consistent with observations made on human.

However, it is important to use these genomic criteria for species delineation with care, and preferably together with morphological and ecological evidence. A limitation of fixation index is that a high F_{ST} may be caused by very low intra-population variation, and the low intra-population variation can be caused by severe bottleneck and genetic drift (Wolf and Ellegren, 2017) or sampling of closely related individuals, such as siblings. Calculation of I_{GF} (details in Methods) does not involve intra-population variations, and thus it should be used to compensate analyses based on F_{ST}. We tested whether these criteria result in false identification of species using populations of the same species from distant localities (Table S2). By the F_{ST} criterion alone, 7% of conspecific population pairs will be candidates for different species, but by both the F_{ST} and I_{GF} criteria, none of these pairs will be regarded as different species. In rare cases, it is possible that when only the conspecific populations at the extremes of a species' distribution range are sampled, they may show high F_{ST} and low I_{GF}, leading to wrong identification of species by our criteria. We thus recommend broad sampling of populations from various localities and computing F_{ST} and I_{GF} for all pairs of populations to obtain a better understanding of the population structure. Confident species delineation can then be achieved by identifying the geographical boundary (if any) separating neighboring populations with high F_{ST} and low I_{GF}.

Similarly, $F_{ST} < 0.10$ and $I_{GF} > 0.09$ for Z-linked genes between allopatric or parapatric populations of butterflies usually indicate that they are conspecific. Rare yet interesting exceptions may exist, because the species boundary can theoretically be maintained through just a handful of key players at the early stage of speciation. In this case, while several important speciation genes are well separated between species, the vast majority of genes may not be able to distinguish specimens of different species, especially for sympatric species. F_{ST} between 0.1 and 0.3, and I_{GF} between 0.025 and 0.09, computed on Z-linked genes, represent the grey zone for species delineation. These challenging cases are better studied individually, through broad sampling of all closely related species of this genus throughout their distribution ranges. The standards for species delineation can be established based on unquestionable species pairs in the genus, which can then be applied to classify other populations of the genus. In addition, morphological, ecological, and phylogenetic evidence should be considered to make sensible judgement regarding species boundaries. One possible reason for different species to have low F_{ST} and high I_{GF} (thus will not pass out criteria of $F_{ST} > 0.30$ and $I_{GF} < 0.025$) in the Z chromosome is that a new species may rapidly originate through hybridization between existing species. In cases of hybrid species, the hybrid may not be well-separated in Z chromosome from one of the parental species.

A region of the cytochrome C oxidase subunit I (COI) gene in the mitochondrial genome has been routinely used as a barcode to identify species, and sequence divergence larger than 2% in the COI barcode has been suggested as a cutoff to differentiate species (Hebert et al., 2003). We tested the ability of the COI barcode to distinguish the pairs of different species from conspecific pairs. Indeed, divergence in the barcode (x-axis in Fig. 2B) separates the true species pairs from the negative controls better than the overall average divergence of nuclear genes (y-axis in Fig. 2B). In addition, any pair with a barcode divergence larger than 2% are different species. However, 8 out of the 15 pairs of different species show barcode divergence below 2%, suggesting a poor sensitivity of COI barcode-based species delineation and calling for the need of nuclear genomes in defining species boundaries, identifying new species, and investigating biodiversity. Problems of using the COI barcode to delineate species have been widely discussed before (Dasmahapatra et al., 2010; Hausmann et al., 2013), but the false negative cases of species differentiation by barcode may be underestimated since there may be new species that are cryptic both in morphology and barcode.

Putative molecular mechanisms of speciation

Genomic analysis of incipient species shows that their divergence is frequently concentrated in certain genomic regions, termed "genomic islands of speciation" or "genomic islands of divergence" (Harr, 2006; Ravinet et al., 2018; Takuno et al., 2019; Turner et al., 2005). Similarly, we set out to identify proteins that have diverged rapidly between species but retained relatively low polymorphism within species by high F_{ST} and significant enrichment of positions that show low polymorphism within, but are divergent between species. We call such proteins divergence hotspots. High F_{ST} values were frequently used to identify "genomic islands of speciation", and a drawback of this measure is that it may bias towards loci with reduced diversity rather than elevated divergence (Cruickshank and Hahn, 2014). Therefore, we also required the selected divergence hotspots to be enriched in positions that are divergent between species.

We carried out this analysis on protein sequences because nonsynonymous substitution in protein-coding sequences are not likely to cause phenotypical changes or contribute to the reproductive isolation between species. These divergence hotspots are not necessarily the drivers for speciation, since their divergence may happen after the establishment of reproductive barrier (Nosil and Schluter, 2011), but they likely include speciation genes. A divergence hotspot from one species has a higher chance to be incompatible with the genetic background of a sister species, thus contributing to postzygotic isolation by causing Bateson-Dobzhansky-Muller hybrid incompatibility (Bateson, 1909; Dobzhansky, 1934; Muller, 1942). In addition, they may be related to the phenotypic divergence between species, which is subjective to sexual selection and contribute to prezygotic isolation. Our criteria tend to identify genes that do not introgress between species, and these divergence hotspots are significantly (P-value < 0.01) depleted of introgressed regions (detected by G_{min}) and are possibly important in maintaining the genetic integrity of different species.

Divergence hotspots constitute about 2% ~ 10% of all transcripts in each pair of species. We mapped these transcripts to Flybase (Garapati et al., 2019), so that we can compare them across different pairs. Every species pair shows higher than random overlap in divergence hotspots with every other species pair, and this overlap is statistically significant ($p < 0.05$) for 90% of cases (Table S3). As negative controls, we identified the divergence hotspots using the same criteria in the conspecific population pairs. Each conspecific pair rarely (the chance is 7%) shows significant ($P < 0.05$) overlap in divergence hotspots with any other conspecific pair or pair of different species (Table S3). This data suggests that speciation of butterflies across the TX suture zone may be associated with the divergence of a similar set of genes that do not readily diverge between conspecific populations.

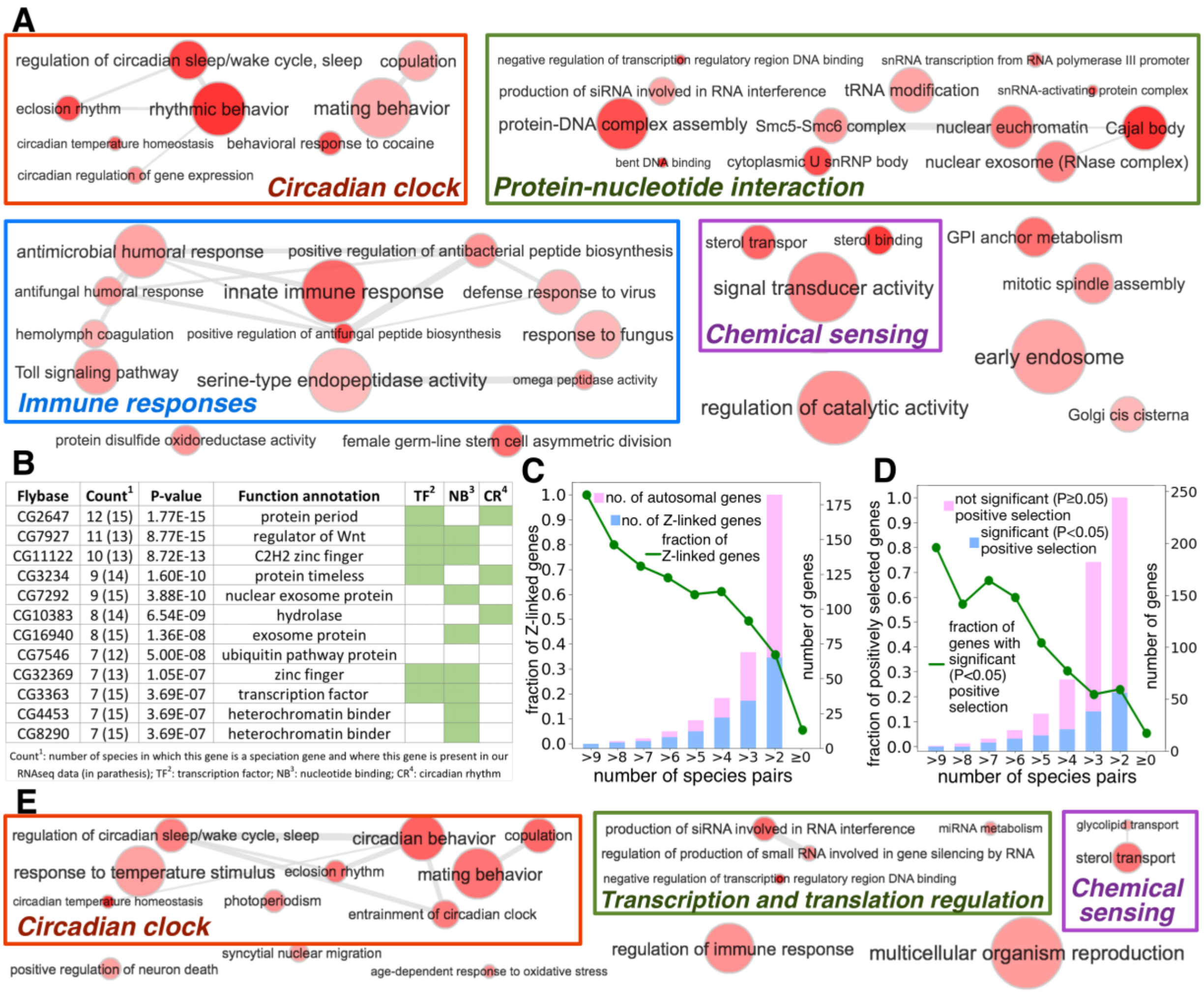

Fig. 3. Common molecular mechanisms of speciation. (A) Functional enrichment of the recurring divergence hotspots reflected by GO terms. (B) Divergence hotspots recurring in the largest number of different species pairs. P-values indicate the probability of observing a protein at this frequency by random chance. The last three columns in the table indicate whether this protein is a transcription factor, nucleotide-binding protein, or circadian clock protein, respectively. (C) Fraction (green curve) and number (blue portion of the bars) of Z-linked genes among the recurring divergence hotspots. (D) Fraction (green curve) and number (blue portion of the bars) of the recurring divergence hotspots that are positively selected. (E) Functional enrichment of the positively selected (P-value < 0.05) recurring divergence hotspots reflected by GO terms.

We find 244 genes that are recurrently ($p < 0.05$) detected as divergence hotspots in multiple pairs of species (Table S4), and the most prominent recurring divergence hotspots are shown in Fig.3B. Protein PERIOD, a key component of the circadian clock system, is among divergence hotspots for 12 out of the 15 species pairs. We observe that the most prominent divergence hotspots tend to have similarity in function. For example, 6 out of the 12 these genes (Fig.3B) are *trans*-regulatory elements and encode transcription factors, 8 of them encode proteins that interact with DNA or RNA, and 3 belong to circadian clock system. We further analyzed the functional enrichment (Table S5) of all 244 recurring divergence hotspots using Gene Ontology (GO) terms and clustered these GO terms by similarity in their meanings (Fig. 3A). This analysis reveals that divergence in circadian clock systems, protein-nucleotide interactions, immune responses, and chemical sensing may be common molecular mechanisms associated with speciation of butterflies across the central TX suture zone.

Lepidoptera use chemicals, namely pheromones, to attract and select mates (Andersson et al., 2007; Pinzari et al., 2018; Raina and Klun, 1984). Some of the recurring divergence hotspots encode sterol binding and sterol transporting proteins that may bind and transport pheromone molecules and thus directly mediate prezygotic isolation between species. Divergence in immune responses may be an adaptive response to exposure to different pathogens during the time of allopatric speciation, but this divergence may also play an active role in prezygotic isolation. In *Drosophila*, males inject sex peptides into females during mating, which causes a range of physiological changes in the females, including difference in sperm management, morphology and hormone level, decreased sexual receptivity, increased egg-laying and feeding (Chapman, 2008; Chapman et al., 1995). Mating also activates the immune system of females (Hollis et al., 2019; Peng et al., 2005), protects them from possible immunogenic attacks, and thus enhances their chance to safely produce the offspring. Mating between individuals of different species may not activate the immune system and cause other physiological changes to the same extent as individuals from the same species due to a lower compatibility between sex peptides and their receptors, including innate immune receptors, from different sources. This incompatibility may reduce the fitness of females mated with males of a different species.

The importance of protein-nucleotide interaction in speciation may arise from postzygotic isolation due to Bateson-Dobzhansky-Muller hybrid incompatibility (Bateson, 1909; Dobzhansky, 1934; Muller, 1942). Different components of the same protein-protein or protein-nucleotide complex coevolve within each species to maintain the structure and function of the complex. If two populations have spent significant time in geographic isolation, different components of the same complex evolve independently and may lose the ability to properly interact and function. This loss might lead to hybrid incompatibility and thus contribute to the reproductive barrier. One limitation of this study based on transcriptomes is that we do not explicitly analyze *cis*-regulatory (non-coding) elements, while diversification in transcriptional regulation has been shown to play a vital role in *Drosophila* speciation (Mack and Nachman, 2017; Orr, 2005; Wu and Ting, 2004a). However, due to the co-evolution between transcription regulatory regions and transcription factors, divergence in *cis*-regulatory elements during speciation is likely accompanied by divergence in transcription factors (i.e. proteins encoded by *trans*-regulatory elements) targeting these *cis* elements. Indeed, transcription factors, and other proteins regulating translation stand out as recurrent divergence hotspot in butterfly species across the central TX suture zone, which is consistent with the findings in *Drosophila*. The possible divergence in trans-regulatory elements may also contribute to prezygotic isolation by controlling developmental processes and generating the different phenotypes that are subjective to sexual selection.

In addition, recurring divergence hotspots show a strong tendency (P-value: 3.08e-35) to be encoded by the Z chromosome, and the most frequently (at least 9 out of 15 pairs) observed divergence hotspots are all Z-linked (Fig. 3C). The importance of the sex chromosome in speciation has been long recognized

(Coyne, 1992b; Coyne, 2018; Haldane, 1922; Prowell, 1998) and is discussed in more detail below. Finally, the existence of divergence hotspots between species is at least partly driven by positive selection. We identified positively selected genes using McDonald–Kreitman (MK) tests (Table S6) (McDonald and Kreitman, 1991), which detect genes showing elevated nonsynonymous substitution rates between species compared to within species. A significant portion (23%) of recurring divergence hotspots (23%) are positively selected ($P < 0.05$), much larger (P-value: 8.1e-21) than the fraction of positively selected genes in the entire transcriptome (5.3%, Fig. 3D). Two thirds of the most prominent recurring divergence hotspots in Fig. 3B are positively selected. Previous studies suggest that speciation genes are typically fast evolving and positively selected (Orr, 2005; Tang and Presgraves, 2009). Therefore, we expect the recurring divergence hotspots showing significant (P-value < 0.05) sign of positive selection (Table S7) to have even higher chance to include speciation genes, and we call them positively selected divergence hotspots. Functional enrichment of these positively selected divergence hotspots further supported the role of circadian clock, transcription and translation regulation and chemical sensing in speciation.

Circadian clock proteins may play a role in speciation

All four key components of the circadian clock system (Fig. 4A), CLOCK (CLO), CYCLE (CYC), PERIOD (PER), and TIMELESS (TIM), are among the recurring divergence hotspots we identified, with PERIOD being the most prominent one. Studies in *Drosophila* show that expression of PER and TIM are activated by CLO and CYC, and accumulation of PER and TIM lead to formation of the PER/TIM complex, which is then transported to the nucleus and suppresses the transcription factor activity of CLO and CYC (Hardin, 2005; Young, 1998). Circadian clock proteins are suggested to be directly involved in courtship behavior: they control the daily rhythm of mating behavior (Sakai and Ishida, 2001) and the species-specific mating song (Emmons and Lipton, 2003) in *Drosophila*.

We mapped the variations (shown as cyan sticks in Fig. 4B) occurring in each pair of species onto the 3D structure of *Drosophila* PER (King et al., 2011). We identified positions (magenta spheres in Fig. 4B) with variations in more than one pair of species (recurring variations), and they concentrate in the second PAS domain of PER, which interacts with TIM (Hennig et al., 2009). Positions suggested to be crucial for the *Drosophila* PER/TIM interaction in mutagenesis experiments (Hennig et al., 2009) are shown as black spheres in Fig. 4B, and several recurring variations are adjacent to these positions. These variations may modulate the binding affinity between PER and TIM, alter the circadian rhythms of different species and contribute to their adaptation to different climate and photoperiod. Due to the important role of circadian clock proteins in mating rhythm (Allada and Chung, 2010; Merlin et al., 2007), divergence in clock proteins may make different species incompatible in their preferred mating time and lead to prezygotic isolation. Furthermore, divergence in circadian clock genes can potentially lead to postzygotic isolation through Bateson-Dobzhansky-Muller hybrid incompatibility (Wu and Ting, 2004b). PER and TIM of the same species are expected to coevolve and maintain proper affinity to trigger the formation of the PER/TIM heterodimer at the right time, ensuring the 24-hour sleep-wake cycle. This 24-hour cycle probably accommodates crucial daily activities such as feeding and mating. However, in a hybrid individual with PER and TIM from different species that have not been evolving together, dimerization between PER and TIM might be affected, impairing the 24-hour cycle and reducing the fitness of the hybrid.

Possible contribution of clock proteins to both prezygotic and postzygotic isolation make them potentially good markers for speciation in butterflies, especially those that are or have been separated by different latitudes. We computed F_{ST} for circadian clock genes and for each of the 25 pairs of species or populations across the central Texas suture zone (Fig. 4C), and observed a much higher F_{ST} for pairs that are different species than conspecific pairs, with only a few exceptions such TIM and CLO in *Phoebis,* and

CLO and PER in *Libytheana.* It is important to note that divergence in circadian clock is not a necessary outcome of population separating into different latitudes. For example, we computed the F_{ST} for populations of *Pterourus glaucus* in different latitudes and geographic regions (Indiana, Virginia-West Virginia, and Texas, separated by 1000 miles). These populations do not show divergence in circadian clock genes (last three rows, #26-28 in Fig. 4C), despite signs of adaptation to latitudes as reflected by the difference in the number of generations per year (Cong et al., 2015b). In contrast, the species pair *P. glaucus* and *P. alexiares* (#15 in Fig. 4C) reveals a notable difference in the clock proteins despite smaller distance between these populations (300 miles).

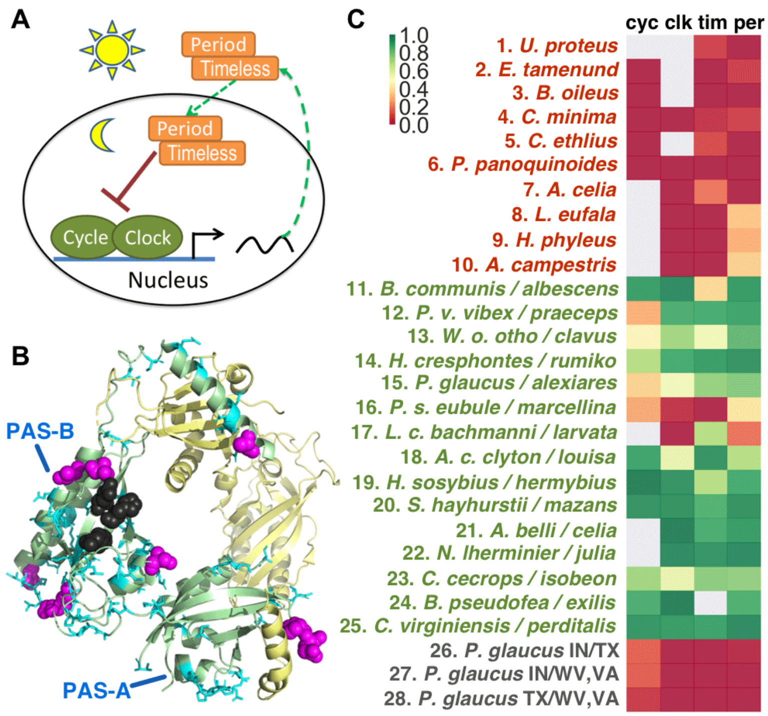

Fig. 4. Circadian clock proteins may play a role in speciation. (A) a schematic of the circadian clock system. (B) Variations in protein PERIOD between species pairs mapped to the 3D structure (PDB id: 3RTY). The structure includes the two PAS domains of PER: PAS-A and PAS-B. Positions that differ in one pair of species are shown as cyan sticks and those that differ in more than one pair are shown as magenta spheres. Residues that disrupt the interaction between PER and TIM are shown as black spheres. (C) F_{ST} (red - low, green - high) of the 4 circadian clock proteins for 25 pairs of counterparts across central Texas suture zone and for populations of *Pterourus glaucus* at different latitudes. Genes whose transcripts are absent in the RNA-seq dataset are shown as gray squares.

The role of Z chromosome in speciation

The important role of sex chromosomes in speciation has been implied since Haldane, who observed that the heterogametic sex among F1 hybrids usually have a higher chance to be sterile or inviable than the homogametic sex (Haldane, 1922; Orr, 1997b). Haldane's rule has been shown to be mostly true for butterflies (Orr, 1997a; Presgraves, 2002). Butterflies, similarly to birds, but different from mammals and *Drosophila*, use the ZW sex determination system (Traut et al., 2007), where a female is the heterogametic sex. Therefore, Haldane's rule implies that F1 female hybrids of butterflies are more likely to be sterile than males. Haldane’s rule also suggests that introgression of mitochondria should be limited in butterflies because hybrid females, who can pass the mitochondria from another species down to its offspring tend to be sterile (Sperling, 1990). Another related observation, namely, the “large X effect”, suggests that substituting the X (or Z) chromosome has a much larger effect on hybrid sterility and inviability than autosomes in backcross experiments (Coyne, 1992a, 2018). This “large X (or Z) effect” has been shown in a range of organisms including butterflies (Coyne, 1992a, 2018; Naisbit et al., 2002).

Multiple factors may contribute to Haldane's rule (Orr, 1997b). The dominance theory (Turelli and Orr, 1995) explains Haldane's rule by the incompatibility between an X (or Z) chromosome of one species and the autosomes of another. Heterogametic hybrids are affected by all sex chromosome-linked alleles that can cause incompatibilities, both recessive and dominant. However, homogametic hybrids are only affected by incompatibilities that are dominant (Turelli and Moyle, 2007; Turelli and Orr, 2000). The dominance theory assumes that the alleles leading to hybrid incompatibilities are overall partially recessive, and thus they display larger deleterious effects on heterogametic hybrids (Turelli and Orr, 1995, 2000). Another well-accepted reason for Haldane's rule is faster (faster-male) accumulation of incompatibilities that can cause sterility in males due to more stringent sexual selection on males (Wu and Davis, 1993), which is not true in butterflies that use ZW sex determination. Faster evolution of X chromosome (Charlesworth et al., 1987) has also been suggested to contribute to Haldane's rule, but we do not observe higher divergence (Fig. 5A left) in Z chromosome than autosomes.

Another simpler explanation for Haldane' rule is the mismatch between the X and Y (Z and W) chromosomes of different species that will impair the genetic interactions between them (Coyne, 1985). This simpler hypothesis was not well-supported in experiments done on *Drosophila* (Johnson et al., 1992). However, a study of sex determination in *Bombyx mori* revealed a primary sex-determiner encoded by the W chromosome, a piRNA targeting the Z-linked gene, *Masc*, that controls the biological development of sex differences (Kiuchi et al., 2014). This study suggests that the proper genetic interaction between Z and W chromosomes may be quite crucial in the development of sex-related features in Lepidoptera, and thus the interaction between Z and W may be partly responsible for Haldane's rule in Lepidoptera.

The "large X (or Z) effect" suggests that individuals with introgressed Z-linked genes are more likely to be sterile. Thus, it is harder for Z-linked genes to introgress between species than autosomal genes. Reduced introgression in sex chromosomes have been observed in a number of species including human, monkey, *Drosophila*, and *Heliconius* butterflies (Carneiro et al., 2010; Ellegren et al., 2012; Lawniczak et al., 2010; Martin et al., 2013; Sankararaman et al., 2014). The fraction of introgressed genes in autosomes is 2-4 times the Z chromosome fraction in all 15 pairs of butterflies in TX suture zone (Fig. 5A middle), again supporting the "large Z effect". Gene flow between diverged species increases intraspecific divergence and lowers interspecific divergence. Therefore, elevated introgression in autosomes compared to the Z-chromosome is expected to contribute to the lower F_{ST} in autosomes (Fig. 5A, right). Additional factors may contribute to the lower F_{ST} in autosomes, such as the change of effective population size before and after speciation, which will affect F_{ST} of sex chromosome and autosomes differently (Van Belleghem et al., 2018). The impact of gene flow is also reflected by the much lower intra-specific divergence in the Z chromosome (π_Z) than the autosome (π_A). The ratio between π_Z and π_A is in the range between 0.2 and 0.8 for the 30 species from the 15 species pairs, with an average value of 0.44. The lower π_Z compared to π_A is partly due to the smaller effective population size of Z-chromosomes, which predicts that the ratio π_Z/π_A should be 0.75. A majority of the observed values are much lower than 0.75, which is likely caused by differential introgression between autosomes and Z chromosome.

Sex chromosomes in mammals are shown to be enriched in genes showing sex-biased expression (Khil et al., 2004) and brain-specific genes (Deng et al., 2014). Sex chromosomes of Lepidoptera have been suggested to be enriched in testis-specific genes (Arunkumar et al., 2009) and sperm proteins (Mongue and Walters, 2018). Analysis of Z-linked gene function in butterflies revealed significant enrichment in proteins participating in courtship, wing development, and transcription factors controlling important developmental processes (Fig. 5B). Additionally, Z chromosome is enriched in genes involved in morphogenesis, development of neural systems, and signaling pathways mediated by hormones (Table S8). Such enrichment suggests a prominent role of the Z chromosome in determining traits that are subject to sexual selection and in promoting copulation between individuals with similar Z chromosomes. For example, 3 of the 4 circadian clock genes are encoded by the Z-chromosome in *Heliconius* (Heliconius Genome Consortium, 2012), and thus the Z-chromosome is more important in determining the rhythm of mating. Such functional enrichment suggests that the Z chromosome may also have a more important role in determining mating preference and leading to prezygotic isolation between species, in addition to the postzygotic effect described in Haldane's rule and the “large X effect”.

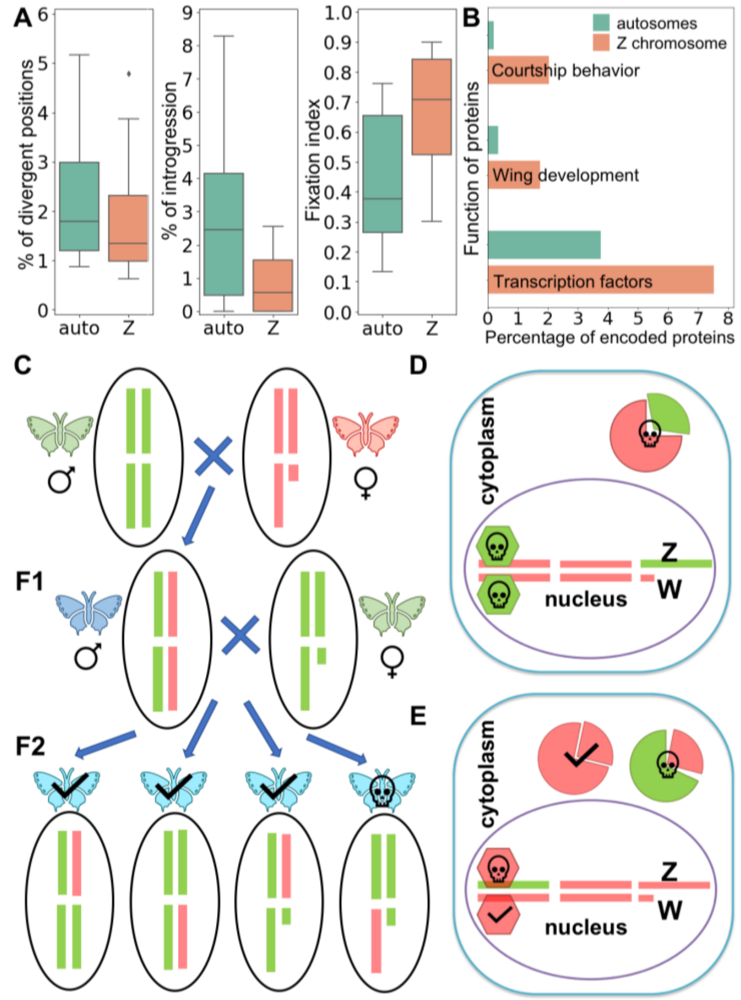

Fig. 5. Role of Z chromosome in butterfly speciation. (A) The level of divergence, introgression and fixation indices for 15 pairs of species computed on autosomes and Z-chromosomes (summarized from values shown in Fig. 2). (B) Z chromosome encodes higher fraction of proteins related to courtship behavior, wing development and transcription factors than autosomes. (C) A model of chromosome introgression explains why Z-chromosome is resistant to introgression. Each individual is marked by a butterfly icon and an oval next to the icon displays its genotype. Green bars mark chromosomes from the green butterfly, and red bars mark those from the red butterfly. Crosses indicate mating. A skull on a butterfly indicates significantly reduced fitness or sterility, while a check indicates a higher chance to survive. (D) and (E): The effect of Bateson-Dobzhansky-Muller hybrid incompatibility is stronger in cases of (D) Z chromosome than (E) autosome introgression. Bars inside the purple circle are chromosomes and hexagons represent transcription factors encoded by Z chromosomes. Cytoplasmic proteins encoded by Z chromosomes are shown as minor sectors while those encoded by autosomes are shown as major sectors. The color of these shapes indicates the origin of these molecules.

Taking the previous theories and our observations, we summarized the role of Z chromosome in Lepidoptera speciation in the following model (Fig. 5C). When two different species (male A and female B) meet, due to the porous reproductive barrier (Mallet et al., 2016), they occasionally mate and produce F1 hybrid offspring. According to Haldane's rule, the F1 female hybrids are more likely to be sterile or inviable. The F1 male hybrids can mate with females of either species A or species B, producing F2 offspring with introgressed autosomes and/or Z chromosome. However, the F2 females with introgressed Z chromosome are expected to have much lower fitness than F2 females with introgressed autosomes according to the “large Z effect”. The incompatibility between Z chromosome and autosomes (as well as W chromosome) of a different species in F2 hybrid females is illustrated in Fig. 5D. This incompatibility is reflected both in protein-protein complexes and protein-DNA complexes. Since the single-copy Z chromosome encodes a number of important transcription factors (TF), the incompatibility between these TFs and the *cis*-regulatory elements from another species will likely have a decisive bad impact on the sterility or fitness of the F2 hybrid females. In contrast, individuals with introgressed autosomes will not suffer as much from the incompatibility of molecules from different origins, because the non-introgressed homologous chromosome of the introgressed autosome can encode proteins that are compatible with the genetic background of the F2 hybrid (Fig. 5E).

This model suggests that in an organism with ZW sex determination, an introgressed Z chromosome has a much lower chance to spread in the population through females. Although males can spread introgressed Z chromosomes, their role in driving the population's gene pool is much weaker because almost every female has the chance of producing offspring, while males compete for the chance of mating and only a fraction succeed. Homologous recombination breaks the linkage of an introgressed segment or chromosome, allowing shorter pieces of foreign Z-linked alleles to spread in the population, but it does not change the fact that on average, introgressed Z-linked alleles may reduce fitness more than autosomes. Occasionally, some introgressed alleles may increase the fitness, and they can spread throughout the population and even completely replace the endogenous alleles due to selective sweeps (Messer and Petrov, 2013). Introgression may be beneficial for a species, despite the expected cost in fitness to an individual in most cases. Even if most of the foreign genes are not compatible with the genetic background of a species, some can bring a selective advantage and allow a species to adapt quickly to different environments, food plants, or pathogens.

MATERIALS AND METHODS

We focused on populations around the central Texas suture zone and assembled 25 pairs of counterparts from both the eastern and western side of the suture zone. For each pair, we gathered from 2 to 15 specimens on each side of the suture zone. The information about the specimens is in Table S1. For samples from the genus *Calycopis*, we used genomic DNA data we published before (Cong et al., 2017; Cong et al., 2016a). For samples from the genera *Phoebis* and *Pterourus*, we used genomic DNA libraries (Cong et al., 2015b; Cong et al., 2016b). For all other genera, we obtained RNA-seq libraries.

Library preparation and sequencing

Specimens for RNA-seq libraries were euthanized upon capture by thorax pinching, and the whole specimen bodies except wings and genitalia were preserved in *RNAlater* solution. Total RNA was extracted from each specimen using QIAGEN RNeasy Plus Mini Kit, and mRNA was further isolated using NEBNext Poly(A) mRNA Magnetic Isolation Module. RNA-seq libraries were prepared with NEBNext Ultra Directional RNA Library Prep Kit following manufacturer's protocol. We pooled RNA-seq libraries of every 12 specimens together and sequenced each pool using one illumina Hiseq2500 lane for 150 bp at each end. Specimens for genomic DNA libraries were either collected in the field (and stored in *RNAlater* or EtOH) or borrowed from collections listed in the Acknowledgements. A piece of thoracic tissue from fresh specimens, and either the abdomen or a leg from pinned museum specimens were used for DNA extraction with Macherey-Nagel NucleoSpin tissue kit following the manufacturer's protocol. Genomic DNA libraries was made using NEBNext Ultra II DNA Library Prep Kit. We pooled DNA libraries according to the expected size of their genome and typically targeted 10-fold sequencing depth for each sample. We sequenced the pooled genomic libraries using Hiseq X ten sequencing service from Genewiz. Sequence data generated in this project were deposited at NCBI under PRJNA601254.

Assembling reference transcriptomes for each case

After removal of contamination from sequencing adapters and the low-quality portion (quality score < 20) of each read using AdapterRemoval (Schubert et al., 2016), we applied Trinity (version r20140413p1) (Haas et al., 2013) to *de novo* assemble the transcriptome separately for each specimen. For each of the 25 cases, we merged the transcripts from all specimens in each pair (they are all closely related) and mapped them to the protein set of a reference genome. We used 6 reference genomes (and the mitogenomes of these species) including *Cecropterus* [formely Achalarus] *lyciades* (Shen et al., 2017), *Calycopis cecrops* (Cong et al., 2016a), *Danaus plexippus* (Zhan et al., 2011), *Heliconius melpomene* (Heliconius Genome Consortium, 2012), *Lerema accius*, (Cong et al., 2015a) and *Pterourus glaucus* (Cong et al., 2015b). For each case, the most closely related reference was used. We applied BLASTX (e-value: 0.00001) (version 2.2.31+) (Altschul et al., 1997) to map the transcripts to protein sequences predicted from the reference genomes. Transcripts that could not find a confident (e-value <= 0.00001) hit among reference proteins were discarded. We filtered the BLASTX hits requiring the aligned positions between the transcript and the hit to cover at least 50% of the residues in the hit, and the remaining hits were ranked primarily by e-value and secondarily by bit score. From the ranked list we identified the best hits that were aligned to non-overlapping regions in the transcript. Usually there was only one best hit per query transcript, and in cases where multiple non-overlapping best hits were identified, the transcript was split to multiple segments corresponding to multiple best hits.

Each transcript was considered to map to the top hit from the reference protein set. Transcripts mapping to the same reference protein were aligned against each other using BLASTN (version 2.2.31+) (Altschul et al., 1997) to remove redundancy and to merge partial transcripts to a complete one. We wanted to represent alternatively spliced isoforms with just the longest isoform, and we removed other isoforms and redundant transcripts from different specimens using the following criteria: (1) if two transcripts were over 95% identical to each other and the aligned region covered at least 80% of one transcript, the shorter transcript was removed; (2) if two transcripts were over 90% identical to each other, their aligned region covered at least 80% of one transcript, and the two transcripts share at least one identical 40mer, the shorter transcript was removed. In order to merge the partial transcripts, we referred to the alignment between transcripts and proteins from reference genomes. If two transcripts were aligned to different portion of the protein with at least 20 residues as overlap, the two transcripts were merged and in the overlapping region, the sequence more similar to the reference protein was taken.

Obtaining sequence alignments

For specimens of *Pterourus*, *Calycopis*, and *Phoebis,* we sequenced the DNA libraries since the reference genomes for these genera were available. We aligned the genomic DNA reads to the reference genomes using BWA (version 0.6.2-r126) (Li and Durbin, 2009) and performed SNP calling with GATK (version 3.3-0) (DePristo et al., 2011). The sequence of each specimen was derived from the GATK results, and the transcript sequences were extracted from these genomic sequences. For specimens of all other genera, where we used RNA-seq reads, a similar pipeline consisting of BWA and GATK was applied using the assembled transcriptomes as references. Transcripts that were covered for at least 60bp by at least two samples from the west and two from the east of the suture zones were kept, resulting in 10675 - 16494 transcripts in each case.

Detecting Z-linked transcripts

High conservation of gene content has been reported in Lepidoptera Z chromosome (Fraisse et al., 2017), and therefore we can deduce the Z-linked genes in other species by comparing to the *Heliconius* *melpomene* reference genome, where Z chromosome sequence was known (Heliconius Genome Consortium, 2012). We identified the Z-linked transcripts in each of the 25 cases using a reciprocal best hit approach. We used BLASTX to search each query transcript against all the *Heliconius* proteins to identify the most closely related hit. If the top hit was a Z-linked protein, we examined whether the hit also found the query transcript as the closest hit by TBLASTN search against all the transcripts from this case. If the answer was yes, we assigned the query transcript as Z-linked.

Designing measurements to separate species from non-species pairs

We mapped the reference transcripts in each case to *Drosophila* proteins in Flybase (Garapati et al., 2019) by identifying the top BLASTX hits, and grouped the transcripts from different cases that were mapped to the same *Drosophila* protein. We kept the groups with transcripts from at least 15 out of the 25 cases, and used the transcripts in these groups to perform the following analysis. For each of the 25 pairs, we computed the fixation index (F_{ST}) and index of gene flow (I_{GF}). We computed these measures both for all the transcripts, and for Z-linked transcripts only. The 25 pairs consist of both different species and conspecific populations, but we use the term "populations" for all pairs below for simplicity. F_{ST} is calculated as $1-\pi_{within}/\pi_{between}$, where π_{within} and $\pi_{between}$ are the average divergence between a pair of specimens from the same population and different populations, respectively. We computed F_{ST} both on DNA sequences of the transcripts and amino acid sequences of the proteins they encode. Since different cases in our study consist of different numbers of individuals, to avoid bias from sample size, we randomly sampled two specimens from each of the two populations to compute F_{ST}. For cases with more than 2 samples from either population, we repeated the random sampling 10 times to increase the chance for each specimen to participate in the calculation.

For each case with two samples from each population, we kept the positions where all 4 samples are present (non-gap) from the sequence alignment of each transcript to compute F_{ST}. We concatenated the filtered alignments for all the transcripts in a case. For the pair of specimens from the same population, we calculated π_{within} as the fraction of positions where they contain different nucleotides (or amino acid for protein-level F_{ST}) out of the all positions in the concatenated alignment. For a pair of populations, we enumerate all possible combinations of a pair of samples from different populations. For each possible combination, we calculated $\pi_{between}$ as the fraction of positions where the two samples contain different nucleotides (or amino acid for protein-level F_{ST}) out of all positions in the concatenated alignment. The values for different combinations were averaged to obtain the $\pi_{between}$ estimation. We calculated the F_{ST} for each of the two populations, and the F_{ST} for this pair is computed as the average of these two populations' F_{ST} values (Bhatia et al., 2013).

One problem with F_{ST} is that a high value can originate from low intra-population divergence caused by bottleneck or sampling of close relatives. Thus, a different measure is needed to overcome this limitation. We therefore detect gene flow between the two populations using G_{min} (Geneva et al., 2015), which detects introgression by very high similarity between the haplotypes of specimens from different populations. G_{min} values are affected by the number of samples. To overcome this problem, we calculated G_{min} for each pair of populations by randomly sampling two specimens from each population. If there are more than two specimens in either population, we repeated the random sampling 10 times and averaged the results to ensure that each sample has a chance to participate in comparisons.

We split each transcript into windows of 1 kb, and extra base pairs at the beginning and end of a transcript were truncated to keep the middle X kb of each transcript, where X is an integer. Transcripts less than 1kb did not participate in the analysis. For each pair of populations, we computed minimal hamming distance (d_{min}) between any pair of specimens from two different populations and the average hamming distance (d_{avr}) between any pair of specimens. We exclude windows with d_{avr} lower than 2, and the remaining number of windows is designated as N_{total}. For each of the remaining windows, we computed the ratio d_{min}/d_{avr}, which is is G_{min}. We considered G_{min} lower than 0.25 to indicate introgression in a window, and total number of such windows is designated as N_{intro}. Since introgression in any of the 4 specimens being analyzed can lead to a low G_{min}, we used $N_{intro}/4 \cdot N_{total}$ to reflect the average fraction of introgressed windows in each specimen, which we term, I_{GF}. We tried different cutoffs of G_{min} from 0.15 (more stringent) to 0.3 (less stringent) to identify the introgressed windows. Changing of the cutoff will change the values of I_{GF}, but does not affect the observed break in I_{GF} values between species and conspecific pairs. We recommend using a cutoff of 0.25 if one wants to use our values in Fig. 2 to calibrate their cases.

Identification of proteins rapidly diverging between species

Our analysis revealed 15 pairs of species across the central Texas suture zone, and we further identified the putative speciation genes for each pair. We hypothesized that the proteins showing significant divergence between species but low polymorphism within each species are more likely to be related to the diversification and the speciation process. We named such genes "divergence hotspots" and identified them using protein sequences they encode by two criteria. First, we calculated F_{ST} on the protein sequences similar to that described above, except here we did the calculation separately on each protein. We ranked all the proteins by the F_{ST} values from high to low, and selected proteins among the top 20% of all proteins covered by the RNA-seq data. This criterion used relative divergence to ensure that the selected proteins were relatively conserved within each species. We considered only the positions where at least 4 sequences (each specimen was represented by two sequences because butterfly genomes are diploid) from each species were not a gap, and we call them informative positions. The total number of informative positions in each protein was denoted as $N_{informative}$. Among informative positions we identified divergent positions that show low polymorphisms within both species but were different between species, and the total number of divergent positions in a protein is denoted as $N_{divergent}$. We considered a position to be conserved within a species if at least 75% of sequences in this species contain the same amino acid, and two species to differ in this position if their consensus amino acids were different. We further identified proteins that were significantly enriched ($p < 0.05$) in such divergent positions. The average rate of divergent positions was calculated as the sum of $N_{divergent}$ over all proteins divided by the sum of $N_{informative}$ over all proteins. The enrichment was quantified using binomial tests. We used the binom_test from the Python scipy module with the following parameters: p = average rate of divergent positions, x = $N_{divergent}$ of this protein, n = $N_{informative}$ of this protein.

In order to identify recurring divergence hotspots, we mapped all the reference transcripts to *Drosophila* proteins in Flybase (Garapati et al., 2019) by identifying the top BLASTX hits. We only considered Flybase entries that were mapped to by transcripts of 9 out of the 15 cases of species pairs. The same set of Flybase entries were used to detect positively selected genes and to study the functional enrichment of the recurring divergence hotspots. We counted how many times each Flybase entry was among the divergence hotspots in all 15 species pairs. If multiple (n) transcripts in one case were mapped to the same Flybase entry, each transcript was counted as 1/n of that entry. Some genes tend to be among the divergence hotspots for multiple cases: when this tendency was significantly larger than random, we considered this gene to be a recurring divergence hotspot. We simulated random processes of selecting x genes in each case, where x was the actual number of divergence hotspots we identified in each case. We repeated the random simulation 10,000 times, and for each gene, we selected 5% of simulations showing the highest frequency for this gene. The lowest frequency of observing the gene among the selected simulations was used as to a cutoff for an observed frequency to be significantly higher than random (P-value < 0.05).

We identified the enriched GO terms associated the recurring divergence hotspots using binomial tests (x = the number of recurring divergence hotspots that were associated with this GO term, n = number of recurring divergence hotspots, p = the probability for this GO term to be associated with any Flybase entry being analyzed). GO terms with P-values lower than 0.05 were considered enriched, and those with P-values less than 0.03 were shown in Fig. 3A. Similar analyses were performed on the positively selected recurring divergence hotspots and all the Z-linked genes.

Detecting positively selected genes between species

We mapped all the reference transcripts in each species pair to *Drosophila* genes (Flybase entries) as described above. For each species pair, we used the alignment of the DNA sequences of each transcript for the following analysis. If multiple transcripts in a species pair were mapped to the same *Drosophila* gene, we concatenated their alignments. We tested whether a gene was positively selected during the divergence of 15 pairs of butterfly species using the McDonald–Kreitman (MK) test (McDonald and Kreitman, 1991). For each species and each gene, we estimated the number of nonsynonymous substitutions (P_N) and synonymous substitutions (P_S) needed to change from the codons of one individual (A) to the codons of another individual (B). If there were multiple substitution paths to change from the codon of A to the codon of B, the path with the smallest number of nonsynonymous substitutions (the most parsimonious) was taken. For each gene, P_N and P_S values for all 30 species in the 15 pairs were summed to get total P_N (TP_N) and P_S (TP_S). Similarly, for each pair of species and each gene, we counted the number of nonsynonymous substitutions (D_N) and synonymous substitutions (D_S) to change from the codons of one species to the codons of another species. The total D_S (TD_S) and total D_N (TD_N) were summed over 15 species pairs for each gene. To calculate the statistical significance for positive selection in each gene, we used Fisher's exact test to compare if TD_N/TD_S was significantly larger than TP_N/TP_S. A gene with P-value less than 0.05 was considered to show significant sign of positive selection.

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