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Normal microRNA Maturation and Germ-Line Stem Cell Maintenance Requires Loquacious, a Double-Stranded RNA-Binding Domain Protein

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partner of Dcr-1. Mutation of loqs in flies and depletion of loqs in Schneider-2 (S2) cells by dsRNA-triggered RNAi disrupt normal pre-miRNA processing. In vivo, loqs is required for robust miRNA-directed silencing and complete target gene repression directed by a transgene expressing dsRNA. Moreover, loss of Loqs function in the ovary disrupts germ-line stem cell maintenance, rendering loqs mutant females sterile.

Results

To identify a dsRBD protein partner for Dcr-1, we searched the conserved domain database [37] for all Drosophila proteins that contain dsRBDS. The protein encoded by the gene CG6866 has two dsRBDS, which are most closely related to dsRBD 1 and 2 of R2D2, suggesting that the two genes are paralogs (Figure 1A). CG6866 and R2D2 are 37% similar and 25% identical in the region of the two dsRBDS. A third dsRBD at the C-terminus of CG6866 was detected using the Pfam collection of protein sequence motifs. This truncated domain deviates from the canonical dsRBD sequence. Because loss of CG6866 function de-silences both endogenous silencing and reporter expression in vivo (below), we named the gene Loquacious, Partner of Drosophila Dicer-1.

![Diagram of RNase III endonuclease protein and dsRBD partner](image1)

**Figure 1.** Loqs, a dsRBD Partner Protein for Drosophila Dcr-1

(A) Each of the three *D. melanogaster* RNase III endonucleases pairs with a different dsRBD protein, which assists in its function in RNA silencing.

(B) Differential splicing creates three *loqs* mRNA variants, *loqs* RA, RB, and RC. *loqs* RA and RB are reported in FlyBase. The RC splice variant is reported here. Arrows mark the position of the PCR primers used in (D); green lines, start codons; red lines, stop codons. The resulting protein isoforms are diagrammed to the right.

(C) Use of an alternative splice acceptor site extends the 5' end of exon 4. The mRNA sequence surrounding the new exon–exon junction is shown, with the *loqs* RC-specific sequence in bold; the arrow marks the position of the last nucleotide of exon 3 relative to the putative transcription start site. When translated into protein, the exon 4 extension inserts 43 new amino acids (indicated below the mRNA sequence) and shifts the Loqs PC reading frame, truncating the protein.

(D) RT-PCR analysis of *loqs* mRNA species in males, female carcasses remaining after ovary dissection, dissected ovaries, and S2 cells. Males express more *loqs* RA than *loqs* RB, female somatic tissue expresses both *loqs* RA and *loqs* RB, while ovaries express predominantly *loqs* RB. *loqs* RC was observed only in S2 cells, together with *loqs* RA and *loqs* RB.

(E) The piggyBac transposon insertion f00791 lies 57 bp upstream of the reported transcription start site for *loqs.*

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loquacious (loqs). loqs is located on the left arm of Chromosome 2 at polytene band 34B9. loqs produces at least three different mRNA isoforms through alternative splicing (Figure 1B). The shortest transcript, loqs RNA splice variant A (RA), encodes a 419-amino-acid protein, Loqs protein isoform A (PA), with a predicted molecular mass of 45 kDa. The transcript loqs RNA splice variant B (RB) contains one additional exon and encodes a protein of 465 amino acids, Loqs protein isoform B (PB), with a predicted molecular mass of 50 kDa. These two mRNA species were identified as cDNAs in the Drosophila genome sequencing project and annotated in FlyBase [38] among the Drosophila proteins that contain dsRBDs. Using non-quantitative RT-PCR, we detected a third splice variant, loqs RNA splice variant C (RC), in which an alternative splice acceptor site for exon 4 is used (Figure 1B, C, and D). Use of the alternative splice site creates a 5'-extended fourth exon and changes the reading frame, resulting in a truncated protein, Loqs protein isoform C (PC), 383 amino acids long (Figure 1C). Loqs PC has a predicted molecular mass of 41 kDa and lacks the entire third dsRBD of Loqs PA and PB (Figure 1B). loqs RA is the predominant mRNA species in dissected testes, whereas loqs RB is the most abundant species in ovaries. Both isoforms are expressed in the carcasses of males and females after removal of the gonads (Figure 1D and data not shown). Using two independent antibodies raised against an N-terminal Loqs peptide, but not using pre-immune sera, we detected a candidate protein for Loqs PC in S2 cells (see below), suggesting that the three loqs transcripts give rise to distinct Loqs protein isoforms.

Thibault and co-workers reported a mutant allele of CG6866, loqs f00791, recovered in a large-scale piggyBac transposon mutagenesis screen of Drosophila [39]. The f00791 piggyBac inserted 57 nucleotides upstream of the loqs transcription start site (Figure 1E); although annotated as lethal, homozygous mutant loqs f00791 flies are viable but completely female sterile. Precise excision of the f00791 piggyBac transposon fully reverted the female sterility (data not shown). Analysis by quantitative RT-PCR using primers that

Figure 2. Loss of Loqs Function Increases the Steady-State Concentration of Pre-miRNA
(A) Northern analysis of total RNA from wild-type, loqs f00791 heterozygotes and homozygotes, and r2d2 heterozygotes and homozygotes for whole males, probed for miR-277 and bantam. The membrane was first hybridized with the miR-277 probe, stripped and probed for 2S rRNA as a loading control, then stripped again and probed for bantam miRNA. Asterisk: the 2S probe was not completely removed before the hybridization with the bantam probe, resulting in an additional band above the mature bantam RNA.
(B) Total RNA from whole males, female carcasses remaining after ovary dissection, and dissected ovaries was probed for miR-7. As a control for successful dissection, the blot was also probed for miR-277, which is not expressed in ovaries (KF and PDZ, unpublished results). 2S rRNA again served as a loading control.
(C) Depletion of dcr-1 or loqs in S2 cells by RNAi leads to pre-miRNA accumulation. Total RNA was isolated after dsRNA-triggered RNAi of the indicated genes. The control sample was treated with dsRNA corresponding to the polylinker sequence of pLitmus28i.
(D) Depletion of Dcr-1, Dcr-2, Loqs, and Drosha was confirmed by Western blotting.
(E) Western blotting analysis demonstrates that Dcr-1 levels are not significantly reduced by depletion of Loqs by RNAi in S2 cells, but are lower in loqs f00791 mutant ovaries.

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amplify all three loqs mRNA splice variants (see Materials and Methods) showed that somatic female loqs f00791 tissues express approximately 5-fold (4.76 ± 0.24; n = 3) less loqs mRNA than wild-type, while loqs f00791 mutant ovaries express approximately 40-fold (42 ± 0.33; n = 3) less loqs mRNA than wild-type ovaries. Testes express approximately 3-fold (2.9 ± 0.5; n = 3) less loqs mRNA in the loqs f00791 mutant than in wild type. These data suggest that the mutant phenotype should be strongest in ovaries, consistent with the mutation causing female sterility as its most obvious defect.

In Vivo, Normal Pre-miRNA Processing Requires Loqs
To assess the function of loqs in miRNA biogenesis, we isolated total RNA from loqs f00791 males and determined the steady-state levels of mature and pre-miRNA for miR-277 and bantam (Figure 2A), which are both expressed in adult tissues. We detected a 100-fold increase in pre-miR-277 and a 12-fold increase in pre-bantam RNAs in homozygous mutant loqs f00791 males, but not in heterozygous loqs f00791 or heterozygous or homozygous r2d2 mutant males. In contrast, the amount of mature miR-277 or bantam was only slightly reduced in the loqs f00791 homozygotes.

Since loqs mRNA expression is lowest in the ovaries of loqs f00791 mutant flies, we analyzed the levels of pre-miR-7 and mature miR-7, a miRNA that is expressed in whole males, manually dissected ovaries, and the female carcasses remaining after removing the ovaries (Figure 2B). While pre-miR-7 increased in all loqs f00791 homozygous mutant tissues, relative to wild-type or loqs heterozygotes, the disruption of miR-7
production in ovaries was striking: not only did pre-miR-7 accumulate, but also mature miR-7 was dramatically reduced. These data suggest that Loqs protein function is required for the maturation of miRNA and demonstrate a direct correlation between losq mutant allele strength and disruption of miRNA processing.

**Loqs Is Required for Pre-miRNA Processing in Drosophila S2 Cells**

To confirm the function of losq in pre-miRNA processing, we depleted cultured *Drosophila* S2 cells of losq mRNA by RNAi (Figure 2C). Eight days after incubating S2 cells with dsRNA corresponding to the first 300 nucleotides of the losq coding sequence, we determined the steady-state levels of pre-miRNA and mature miRNA for miR-277 and bantam. Relative to an unrelated dsRNA control, dsRNA corresponding to *dcr-1* caused a approximately 9-fold and approximately 23-fold increase in steady-state pre-miR-277 and bantam levels, respectively, and dsRNA corresponding to *loqs* caused a approximately 2-fold and approximately 6-fold increase in steady-state pre-miR-277 and bantam levels, respectively. In these experiments, RNAi of *dcr-1* more completely depleted Dcr-1 protein than RNAi of *loqs* reduced Loqs protein (Figure 2D). RNAi of *dcr-2*, *r2d2*, or *drosha* did not alter pre-miRNA levels for either miR-277 or bantam, nor did it alter Dcr-1 or Loqs levels. The Drosha/Pasha protein complex functions before pre-miRNA processing, converting primary miRNA (pri-miRNA) to pre-miRNA. Consistent with the idea that Loqs functions with Dcr-1 to convert pre-miRNA to mature miRNA, RNAi of *drosha* together with *loqs* alleviated the high pre-miRNA levels observed for RNAi of *loqs* alone, demonstrating that Loqs acts after Drosha.

Next, we examined processing of 20 nM exogenous pre-let-7 into mature let-7 in lysates from ovaries or S2 cells (Figure 3). Initial velocities were calculated for each reaction to permit comparison of processing rates (see Materials and Methods). Lysate from homozygous *losq* mutant ovaries processed pre-let-7 RNA to mature let-7 approximately 19-fold more slowly than wild-type ovary lysate (Figure 3A). Moreover, lysate prepared from S2 cells soaked with a green fluorescent protein (GFP) control dsRNA (GFP[RNAi]) or *drosha* dsRNA (drosha[RNAi]) accurately and efficiently converted exogenous pre-let-7 RNA into mature let-7. In contrast, both *dcr-1*(RNAi) and *loqs*(RNAi) S2 cell lysates converted pre-miRNA to mature miRNA approximately 5- and approximately 4-fold, respectively, more slowly than the control lysate (Figure 3B). Thus, Loqs is required for production in vivo of normal levels of miR-7, miR-277, and bantam, and the efficient conversion of pre-let-7 to mature let-7 in vitro. Together, these four miRNAs include both miRNAs found on the 5' and on the 3' side of the pre-miRNA stem, suggesting a general role for Loqs in pre-miRNA processing.

Reduction of R2D2 protein by RNAi destabilizes Dcr-2; conversely, RNAi of Dcr-2 renders R2D2 unstable [21]. In contrast, RNAi of *losq* in S2 cells reduced Dcr-1 protein levels by no more than 15% (Figure 2D and E), suggesting that Loqs functions together with Dcr-1 in pre-miRNA processing, rather than that Loqs is simply needed to stabilize Dcr-1 protein. However, *losq* mutant ovaries, which lack detectable Loqs protein, contain 70% less Dcr-1 than wild-type (Figure 2E). A role for Loqs in both Dcr-1 function and in Dcr-1 stability suggests that the two proteins physically interact, like R2D2 and Dcr-2. Therefore, we tested if Dcr-1 and Loqs are components of a common complex.

**A Dcr-1 Protein Complex Contains Loqs**

We expressed in S2 cells myc-tagged versions for two protein isoforms of Loqs, Loqs PA and Loqs PB, and immunoprecipitated the tagged proteins with anti-myc monoclonal antibodies. We analyzed the immunoprecipitated protein by Western blotting using a polyclonal anti-Dcr-1 antibody. Figure 4A shows that Dcr-1 protein co-immunoprecipitated with myc-tagged Loqs. When myc-tagged GFP was expressed in place of myc-tagged Loqs, no Dcr-1 protein

![Figure 5. Loqs Is Associated with Pre-miRNA Processing Activity in S2 Cells](image-url)
was recovered in the anti-myc immunoprecipitate. Similarly, an affinity purified, polyclonal antibody directed against the N-terminus of endogenous Loqs protein also co-immunoprecipitated Dcr-1 protein (Figure 4A). This interaction was resistant to treatment with RNase A (data not shown). We could not detect co-immunoprecipitation of Dcr-2 with myc-tagged Loqs PB under conditions where Dcr-1 was readily detected (Figure 4B), but we cannot exclude that Dcr-2 is a substoichiometric component of a complex that contains both Dcr-1 and Loqs (see below).

When immunoprecipitated with anti-Dcr-1 antibody, both myc-tagged Loqs protein isoforms—PA and PB—associated with Dcr-1 (Figure 4C). Moreover, the antibody against endogenous Loqs protein detected two bands corresponding

Figure 6. Analysis of Complexes Containing Pre-miRNA Processing Activity, Dcr-1, and Loqs

(A) S2 cell lysate was fractionated by gel filtration chromatography and analyzed for pre-let-7 processing activity, and Dcr-1, Dcr-2, and Loqs proteins. (B) The sizes of the distinct complexes containing Loqs (~630 kDa), Dcr-1 (~480 kDa), and Dcr-2 (~230 kDa) and the broad complex containing pre-miRNA processing activity (~525 kDa) were estimated using molecular weight standards (thyroglobulin, 669 kDa; ferritin, 440 kDa; catalase, 232 kDa; aldolase, 158 kDa; bovine serum albumin, 67 kDa; ovalbumin, 43 kDa; chymotrypsinogen A, 25 kDa) and recombinant Dcr-2 and R2D2 proteins (rDcr-2 and R2D2). The blue asterisk denotes the peak of pre-let-7 processing activity detected in (A). (C) Fractions containing the Dcr-1 peak were pooled and immunoprecipitated with either anti-Dcr-1 or anti-Loqs antibodies. Western blotting with anti-Dcr-1 and anti-Loqs antibodies demonstrated that Dcr-1 and Loqs remained associated through gel filtration chromatography.

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Figure 7. Silencing of a miRNA-Responsive YFP Reporter Requires loqs but Not r2d2

(A) A YFP transgene expressed from the Pax6-promoter showed strong fluorescence in the eye and weaker fluorescence in the antennae. Due to the underlying normal red eye pigment, the YFP fluorescence was observed in only those ommatidia that are aligned with the optical axis of the stereomicroscope. In heterozygous loqs^{f00791}/CyO flies bearing a miR-277-responsive, Pax6-promotor-driven, YFP transgene, YFP fluorescence was visible in the antennae but was repressed in the eye. In contrast, in homozygous mutant loqs^{f00791} flies, YFP fluorescence was readily detected in the eye. A strong mutation in r2d2 did not comparably alter repression of the miR-277-regulated YFP reporter. The exposure time for the unregulated YFP reporter strain was one-fourth that used for the miR-277-responsive YFP strain. The exposure times were identical for the heterozygous and homozygous loqs and r2d2 flies. (B) Additional images of eyes from loqs^{f00791} heterozygous and homozygous flies bearing the miR-277-responsive YFP reporter transgene diagrammed in (A).
Quantiﬁcation of ﬂuorescence of the miR-277-responsive YFP transgene in eyes heterozygous or homozygous for loqs or r2d2. The maximum pixel intensity was measured for each eye (excluding antennae and other tissues where miR-277 does not appear to function). The graph displays the average \( (n = 13) \) maximum pixel intensity ± standard deviation for each homozygous genotype, normalized to the average value for the corresponding heterozygotes. Statistical signiﬁcance was estimated using a two-sample Student’s \( t \)-test assuming unequal variance.

The images in (A) were acquired using a sensitive, GFP long-pass ﬁlter set that transmits yellow and red autoﬂuorescence. Images in (B) and for quantitative analysis were acquired using a YFP-speciﬁc band-pass ﬁlter set that reduced the autoﬂuorescence recorded.

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Loquacious, Partner of Drosophila Dicer-1

(A) The red eye color of wild-type flies (left) changes to orange (center) and white (right) in response to one or two copies, respectively, of a white IR transgene, which silences the endogenous white gene. (B) Homozygous mutant r2d2 flies fail to silence white, even in the presence of two copies of the white-IR transgene; heterozygous r2d2/Cyo flies repress white expression. (C) In flies homozygous for loqs(fo0791), silencing of white by the white-IR is less efficient; two copies of the white-IR do not produce completely white eyes, whereas they do in heterozygous loqs(fo00791)/Cyo. (D) The eye color change in loqs(fo00791) flies is not caused by the increased white gene dose resulting from the mini-white marker in the piggyBac transposon that causes the loqs(fo00791) mutation. Flies trans-heterozygous for loqs(fo00791) and a mini-white-marked P-element have more red eye pigment than loqs(fo00791) homozygous flies, but show more efficient silencing by the white-IR than loqs(fo00791) homozygous animals. (E) The eye pigment of the indicated genotypes was extracted and quantified by green light (480 nm) absorbance, relative to wild-type flies bearing no white-IR transgenes. The graph shows the mean and standard deviation of five independent measurements per genotype.

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Figure 8. Silencing of white by an IR Partially Depends on loqs

The loqs(fo00791) mutation caused pre-miRNAs to mature miRNA (Figure 5). Pre-miRNA processing by the immunoprecipitates was efficient and accurate when we used the anti-Dcr-1 antibody (Figure 5A), and when we used anti-myc antibody and expressed myc-tagged Loqs, but not when we used the antimyc antibody and expressed myc-tagged GFP (Figure 5A and 5B). Thus, Dcr-1 and Loqs co-associate in a complex capable of converting pre-miRNA into mature miRNA. Our data also demonstrate that an N-terminal tandem myc tag does not perturb Loqs function in pre-miRNA cleavage.

Next, we estimated the size of the pre-miRNA processing complex by gel filtration chromatography. Pre-miRNA processing activity chromatographed as a broad approximately 525-kDa peak that overlapped the peaks of both Dcr-1 and Loqs proteins (Figure 6A and 6B). Dcr-1 protein chromatographed as an approximately 480-kDa complex that overlapped the peak of Loqs PB, which chromatographed as an approximately 630-kDa complex. The Loqs PB isoform accounts for most of the Dcr-1-associated Loqs in S2 cells (see Figure 4D). The apparent size of the Dcr-1 complex suggests that it is either associated with proteins in addition to Loqs or that the complex has an elongated shape that increases its apparent molecular weight. Pre-miRNA processing activity, Loqs, and Dcr-1 were all well resolved from the approximately 230-kDa peak of Dcr-2 (theoretical mass \( \approx 197.7 \) kDa), which corresponds to the Dcr-2/R2D2 heterodimer (theoretical mass \( \approx 232.7 \) kDa). Although the peaks of Loqs and Dcr-1 do not co-migrate, Dcr-1 was stably associated with Loqs after gel filtration: Dcr-1 and Loqs reciprocally co-immunoprecipitated from the pooled peak Dcr-1 fractions (Figure 6C). Loqs was not detected in the Dcr-2 peak by this method (data not shown). Loqs PC, which did not associate with Dcr-1 in immunoprecipitation, chromatographed as a 58-kDa protein, suggesting that it is a free monomeric protein (data not shown).

A Loqs Mutation Reduces Silencing of a miRNA-Controlled Reporter Transgene In Vivo

The loqs(fo00791) mutation caused pre-miRNAs to accumulate in the soma and the germ line and strongly reduced mature mir-7 levels in the female germ line, suggesting that Loqs function is required for miRNA-directed silencing in vivo. We introduced a miRNA-regulated yellow fluorescent
protein (YFP) reporter into loqs<sup>00791</sup> homozygous mutant flies. This transgenic reporter expresses in the eye a YFP mRNA bearing four miR-277 binding sites in its 3' UTR. The four miRNA-binding sites pair with all but the central three nucleotides of miR-277 and are, therefore, predicted to repress reporter mRNA translation rather than trigger mRNA cleavage (Figure 7A). YFP fluorescence was readily detected in the eye and antennae in control flies in which the 3' UTR of the YFP transgene lacked the four miR-277 binding sites (Figure 7A). When the reporter contained the miR-277 binding sites, YFP expression was repressed in the eye but readily visible in the antennae, indicating that miR-277 is expressed in the eye (loqs/CyO, Figure 7A and B). This expression was verified independently by Northern blots of RNA isolated from eyes dissected away from other tissues of the head (data not shown). Silencing of the miR-277-responsive YFP reporter in the eye was reduced in loqs<sup>00791</sup> homozygous mutant flies (log10loqs, Figure 7A, B and C). As a control, we examined the effect of a strong r2d2 mutation on YFP reporter expression (Figure 7A and C). We measured the maximum fluorescence intensity in each eye for all four genotypes. Figure 7C shows that there was a significant (P < 1.9 × 10<sup>−7</sup>) increase in YFP fluorescence in eyes homozygous for the weak hypomorphic allele loqs<sup>00791</sup>. This allele reduced miR-277 levels in the soma approximately 2-fold (see Figure 2B); fluorescence in the eye of homozygous mutant loqs flies was 1.8 ± 0.17 (average maximum intensity ± standard deviation; n = 13) times greater than in the eyes of their age-matched heterozygous siblings. In contrast, flies homozygous for a strong hypomorphic r2d2 mutation show only a modest change in fluorescence (1.1 ± 0.09; n = 13; P < 0.025). The Dcr-2 partner protein R2D2 is required for RNAi triggered by exogenous dsRNA [21] or transgenes expressing long dsRNA hairpins (see below and Figure 8). We conclude that the reduced levels of Loqs protein in the loqs<sup>00791</sup> mutant lead to a statistically significant reduction in miRNA-directed silencing and that the Loqs paralog R2D2 plays little, if any, role in miRNA function.

Loqs Participates in Silencing Triggered by Long dsRNA In Vivo

dsRNA transcribed as an inverted repeat (IR) triggers silencing of corresponding mRNAs in flies [23,40]. For IR-silencing of the white gene, whose gene product is required to produce the red pigment that colors fly eyes, the extent of silencing is proportionate to the number of copies of the IR-white transgene [23,40] (Figure 8A), but is relatively insensitive to the number of copies of white present (TD and PDZ, unpublished). RNAi in Drosophila requires both Dcr-2, which transforms long dsRNA into siRNA, and R2D2, which collaborates with Dcr-2 to load siRNA into RISC. Thus, IR-silencing of white mRNA is lost in both dcr-2 [23] and r2d2 mutant flies (Figure 8B). We quantified the extent of white silencing by extracting the eye pigment in acidic ethanol and measuring its absorbance at 480 nm (Figures 8E and S1). Loss of R2D2 function in flies expressing one (or two) copies of the white IR transgene and two copies of the endogenous white locus reduced red pigment levels to 74 ± 13 (or 73 ± 15 for two copies of IR-white) percent of wild-type flies lacking the white-IR. loqs<sup>00791</sup> mutant flies were also defective in IR-triggered white silencing, but to a much smaller extent (Figure 8C and 8E). The loqs<sup>00791</sup> mutation restored pigment levels in flies carrying one copy of the white IR-expressing transgene to 12 ± 2% of wild-type and to 8 ± 0.6% for flies carrying two copies of the white-IR (n = 5; Figures 8C and E). loqs<sup>00791</sup> heterozygotes were statistically indistinguishable from wild-type flies bearing one copy of IR-white, whose eye pigment concentration was 4 ± 0.5 (or 2 ± 0.6 for two copies of IR-white) percent of wild-type in the absence of the IR-white transgene.

Insertion of a mini-white-expressing piggyBac transposon causes the loqs<sup>00791</sup> allele. Thus, loqs<sup>00791</sup> heterozygotes have two copies of the endogenous white locus and one copy of mini-white; loqs<sup>00791</sup> homozygotes have two copies of endogenous white and two copies of mini-white. The presence of this additional copy of mini-white does not account for the darker red color of white-silenced loqs<sup>00791</sup> flies, because loqs<sup>00791</sup> heterozygotes bearing two copies of white, one copy of mini-white (in the piggyBac transposon inserted at loqs), and one copy of a P-element expressing mini-white are effectively silenced by IR-white (Figure 8D). In the absence of the IR-white transgene, the total amount of white expression in these flies is higher than in loqs<sup>00791</sup> homozygotes (Figure 8D). Thus, reduction of Loqs function accounts for the partial desilencing of white in this system. The modest loss of silencing in the loqs<sup>00791</sup> mutant flies may reflect the incomplete loss of Loqs protein in this allele. However, Carthew and co-workers previously reported that a dcr-1 null mutation leads to a similar, partial loss of white IR-silencing [23]. The small eye phenotype of dcr-1 null mutants unfortunately renders a quantitative comparison to loqs<sup>00791</sup> impossible. We propose that—as for pre-miRNA processing—Dcr-1 and Loqs act together to enhance silencing by siRNAs.

Figure 9. Silencing of Stellate by the dsRNA-Generator Su(Ste) Requires loqs
Tests were stained for DNA (red) and Stellate protein (green). Defects in RNA silencing often lead to accumulation of Stellate protein crystals in testes. For example, the testes from the strong allele arm<sup>72.1</sup>, but not wild-type Oregon R testes, show Stellate protein staining. Testes from loqs<sup>00791</sup> males show strong accumulation of Stellate protein, consistent with their significantly impaired fertility.

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Silencing of the Endogenous Stellate Locus Requires Loqs

loqs<sup>60791</sup> males are incompletely fertile. When Oregon R females were mated to loqs<sup>90751</sup> homozygous mutant males, only 17% of embryos hatched (n = 479); for loqs<sup>60791</sup> heterozygous males, 47% of embryos hatched (n = 466). Ninety percent of embryos hatched (n = 753) for wild-type Oregon R males. Genes required for RNA silencing often reduce male fertility, because the X-linked gene Ste is epigenetically silenced in testes by dsRNA derived from the bi-directionally transcribed Suppressor of Stellate (Su(Ste)) locus [41]. Ste silencing is genetically similar, but not identical, to RNAi, in that like RNAi it requires the function of the gene armirite (armi) [24], but unlike RNAi does not require 2d2 (VVV and PDZ, unpublished data). In the absence of Ste silencing, Stellate protein accumulates as protein crystals in the testes. loqs<sup>60791</sup> mutants contain Stellate crystals in their testes (Figure 9), much like armi<sup>72,1</sup> mutants, identifying a second role for loqs in silencing by endogenous RNA triggers, distinct from its function in miRNA biogenesis.

A Germ-Line Stem Cell Defect in loqs<sup>60791</sup> Mutant Females

The loqs gene has a critical function in oogenesis, as loqs<sup>60791</sup> females have small ovaries (Figure 10A) and are completely sterile. Drosophila ovaries comprise ovarioles that contain developmentally ordered egg chambers, which are produced continuously in the adult by germ-line stem cell division. As a result, mutations that block stem cell division or maintenance lead to ovarioles containing few egg chambers. loqs<sup>60791</sup> mutant females lay no eggs. Whereas wild-type females contain 7 ± 0.8 (n = 15) previtellogenic egg chambers per ovariole, loqs<sup>60791</sup> contain only 3 ± 0.8 (n = 20). Excision of the piggybac transposon in loqs<sup>60791</sup> restores fertility, demonstrating that these defects reflect loss of Loqs function. The mature oocytes in loqs<sup>60791</sup> ovarioles have normal dorsal appendages, indicating that dorsoventral patterning is normal. In contrast, mutations in armi, spinE, and aub disrupt both dorsoventral and anteroposterior patterning [42–44]. These mutations all disrupt RNAi and Ste silencing, but display no global defects in miRNA biogenesis or function, unlike loqs [24,41,45,46].

Oogenesis is initiated in the gerarium, which contains the germ-line stem cells as well as the early germ-line cysts that will form egg chambers. In loqs<sup>60791</sup> mutant ovarioles, the gerarium generally contain a limited number of cells that stain for Vasa, indicating that they are of germ-line origin (Figure 10B). No mitotic figures were observed, nor were separate cysts. Germ-line stem cells and their daughter cells, the cystoblasts, are characterized by the presence of a spherical structure, the spectrosome, that stains intensely with anti-Spectrin antibodies [47–49]. We stained wild-type and loqs<sup>60791</sup> gerarium with anti-α-Spectrin antibodies (Figures 10C and S2). We could not detect spectrosomes in the loqs mutant gerarium, suggesting that in these gerarium, dissected from flies 3–4 d old, no stem cells remained. Stem cells must have originally been present, because loqs mutant ovarioles produce some late-stage oocytes. Thus, most of the original stem cells may have died or differentiated into cystoblasts without renewing the stem cell pool. At present, we cannot distinguish between these alternatives. We conclude that loqs<sup>60791</sup> mutants, which are defective in three distinct types of RNA silencing, fail to maintain germ-line stem cells.

Discussion

RNase III Endonucleases Act with dsRNA-Binding Partner Proteins in RNA Silencing

Collectively, Dcr-1 and Loqs, Drosha and Pasha, and Dcr-2 and R2D2 comprise six of the 12 dsRBD proteins predicted to be encoded by the Drosophila genome [50]. Thus, at least half of all dsRBD proteins in flies participate in RNA silencing. In
Caenorhabditis elegans, the R2D2-like dsRBD protein RDE-4 is required for RNA interference and interacts with DCR-1, the sole worm Dicer gene [51]. RDE-4 is equally similar to Loqs (E-value = 0.03) and R2D2 (E-value = 0.026; search restricted to C. elegans proteins). The Drosha/Pasha complex is also present in C. elegans [10] as well as cultured human cells [11–13]. Similarly, the Arabidopsis thaliana dsRBD protein HYL1 is required for the production of mature miRNAs, and hyl1 mutant plants have a phenotype similar to that of dicer-like 1 (dcl1) [52,53]. Hiraguri and co-workers [54] recently demonstrated that HYL1 is a dsRNA-binding protein that binds DCL1 and that the HYL1 paralog DRB4 binds the Dicer protein DCL4. Pairing of RNase III endonucleases with dsRBD proteins is thus a recurring theme in RNA silencing.

A dsRBD Partner for Human Dicer?

The human genome encodes one Dicer protein, which is more closely related to Drosophila Dcr-1 than Dcr-2. Sequence analysis of human proteins for similarity to either C. elegans RDE-4 or Drosophila R2D2 does not identify a reasonable candidate for a dsRBD partner protein for human Dicer. In contrast, the human TRBP is highly similar to Drosophila Loqs (E-value = 5 × 10^{-36}). For comparison, the human proteins most similar to R2D2 or RDE-4 give E-values of 8 × 10^{-38} and 0.42, respectively, when the search is restricted to human proteins. Human TRBP was first identified [55] because it binds HIV trans-activator RNA (TAR), a stem-loop structure required for active HIV transcription [56–58]. Remarkably, the secondary structure of TAR resembles a miRNA precursor, and the recent discovery of Epstein-Barr virus-encoded miRNAs [59] has fueled speculation that TAR may be a viral pre-miRNA [60].

Deletion of PRBP, the mouse homolog of TRBP, yields viable mice that often die at the age of weaning. Surviving homozygous mutant males show defects in spermatogenesis attributed to abnormal sperm maturation rather than proliferation [61]. In contrast, Dicer knockout mice show very early embryonic lethality [62]. If mouse Dicer and PRBP collaborate to produce mature miRNA, the essential function of Dicer during mouse development must either be independent of miRNA function, or a redundant factor must be required for active HIV transcription [56–58]. Nonetheless, these two pathways are not completely separate, because cells lacking dcr-1 are not fully competent for IR-triggered silencing [23]. Dcr-1 is not required for siRNA production, yet embryo extracts lacking Dcr-1 fail to assemble RISC [23]. Dcr-1 has been proposed to be a component of “holo-RISC,” an 80S complex containing many, but not all, components of the RNAi pathway in flies [63]. The loqs^{f00791} mutation also reduced the efficiency of IR-triggered silencing in vivo. Therefore, we propose that Dcr-1 must partner with Loqs not only during the processing of pre-miRNA to mature miRNA, but also to ensure Dcr-1 function in the Dcr-2-dependent RNAi pathway.

Carthew and colleagues found no function for Dcr-2 in miRNA biogenesis [23]. Consistent with their results, we found little if any requirement for R2D2 in miRNA-directed silencing (see Figure 7C). Moreover, null or strong hypomorphic alleles of either dcr-2 or r2d2 show no overt phenotype, whereas the dcr-1^{f00728} and loqs^{f00791} null mutations are embryonic lethal [23].

Stellate Silencing Requires Loqs

Endogenous silencing of the Stellate locus in testes is genetically distinct from miRNA-directed silencing, because it requires armiilage, a gene that plays no general role in miRNA biogenesis or function [24]. Stellate silencing resembles RNAi in that Stellate expression is repressed by a dsRNA trigger transcribed from the Su(Ste) gene. Su(Ste) dsRNA produces siRNAs, called repeat-associated siRNAs, that are longer than the siRNAs produced in the RNAi pathway in Drosophila [41]. Even the weak allele described in this study, loqs^{f00791}, which reduces loqs mRNA levels only approximately 3-fold in testes, dramatically de-silences Stellate. Given the intimate association of Dcr-1 with Loqs, our data raise the possibility that Loqs acts to silence Stellate in collaboration with Dcr-1, which may generate the Su(Ste) repeat-associated siRNAs.

Germ-Line Stem Cells and miRNAs

The loqs^{f00791} mutation is the first viable allele in Drosophila with a generalized defect in miRNA production. The allele may therefore be useful for future phenotypic analysis of miRNA-dependent pathways during the life cycle of Drosophila. The most obvious phenotype of loqs^{f00791} is female sterility, loqs^{f00791} homozygotes produce few egg chambers, indicating a defect in germ-line stem cell maintenance or division. The loqs^{f00791} phenotype is similar to mutants in piwi [64], which encodes a member of the Argonaute protein family of core RISC components. In piwi mutant ovaries, germ-line stem cells fail to divide and instead differentiate directly into cystoblasts, depleting the germarium of germ-line stem cells. loqs mutants display a similar phenotype: we did not detect germ-line stem cells (i.e., spermatocyte-containing cells) in loqs^{f00791} homozygous germlaria, suggest-
ing that Loqs is required to maintain stem cells. Piwi is required in terminal filament cells, somatic cells surrounding the tip of the germarium, to send a signal that prevents germ-line stem cells from differentiating [64,65]. Piwi is also required in germ-line stem cells themselves to stimulate their proliferation [65]. Perhaps Piwi is at the core of an effector complex loaded with small RNA produced by Dcr-1 and Loqs. Intriguingly, der-1 knockout mice die at embryonic day 7.5, apparently devoid of stem cells [62].

Materials and Methods

PiggyBac excision. To establish that insertion of the f00791 piggyBac transposon in the female sex of mutants, we excised the transposon by introducing into loop[loqs] loop heterozygotes a transgene expressing the piggyBac transposase from a Hermes element inserted on Chromosome 3 [66]. F1 male progeny of these flies were mated to y, Sc/Cyo virgins, and the resulting F2 progeny screened for loss of white expression (i.e., white eyes). Of 100 F2 progeny examined, one white male could be recovered. A line established from this fly was homozygous female fertile.

Real-time RT-PCR analysis. Two µg of total RNA was reverse transcribed using 5'-GGC GAG AAT TTC CAC GGC-3' and 5'-TTG GAA CAA AAA CTT ATT TCT GAA GAA GAC TTG GCC ATG-3' oligonucleotide as primer and Superscript II reverse transcriptase (Invitrogen, Carlsbad, California, United States). After extension, cDNA samples were diluted 3-fold with water. One µl of diluted cDNA was used for quantitative PCR using the Quantitect SYBR Green PCR Master Mix (QIAGEN). The following oligonucleotide primer pairs were used to obtain gene expression (i.e., white eyes). Amplification efficiencies were identical for both oligonucleotide pairs.

RNA isolation and detection by Northern blot. RNA was isolated from whole flies, dissected organs or S2 cells using Trizol (Invitrogen) according to the manufacturer's instructions. The RNA was quantified by absorbance at 260 nm, and 2-10 µg of total RNA was resolved by electrophoresis through a 20% denaturing acrylamide/urea gel (National Diagnostics, Atlanta, Georgia, United States). After transfer membranes were boiled twice in 0.1% SDS for 1 min in a microwave oven. The following probes were used for detection: 5'-GGC CTC GTC GCT GGG CAA-3' and 5'-AAT TGC TCG ACA TCC CTC C-3' for actin5C. The concentration of dsRNA was estimated by native gel electrophoresis (Bio-Rad). Gene fragments were amplified from the plasmid templates with two 277 synthetic oligonucleotide (Dharmacon, Lafayette, Colorado, United States) was included on the gel. After electrophoresis, the RNA was isolated and detection by Northern blot. The labeled probe oligonucleotide was added to 10 µl reaction; specific activity 7,000 Ci/mmol). To establish that insertion of the f00791 piggyBac transposase from a Hermes element inserted on Chromosome 3 [66]. F1 male progeny of these flies were mated to y, Sc/Cyo virgins, and the resulting F2 progeny screened for loss of white expression (i.e., white eyes). Of 100 F2 progeny examined, one white male could be recovered. A line established from this fly was homozygous female fertile.

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homogenates were placed at 4°C for 30 min. Subsequently, protein α/γ-agarose (Calbiochem, San Diego, California, United States) or anti-rabbit IgG agarose (eBioscience, San Diego, California, United States) was added and the samples agitated at 4°C for 90 min. For RNase treatment, RNase A was added to a final concentration of 50 μg/ml, and the samples incubated for 15 min at 4°C prior to immunoprecipitation. Beads were washed four times with 1 ml of lysis buffer containing 1% (v/v) Triton X-100 (Sigma).

For Western blotting, the proteins were separated on 8% polyacrylamide/SDS gels and transferred to PVDF-membrane. All incubations and washes were in TBS containing 0.02% (v/v) Tween-20. For the rabbit primary antibodies, we used a secondary antibody that does not recognize the reduced form of rabbit IgG (Trueblot, eBioscience), permitting detection of Loqs, which migrates near the heavy antibody chain present in the immunoprecipitates.

To isolate anti-rabbit antibodies, two rabbits were immunized with the KLH-conjugated peptide MQQNFHGGSSC. The specificity of the antibody was verified by Western blotting using extracts prepared from S2 cells transfected with the myc-Loqs PB expression vector, using untransfected S2 cell extract for comparison. Both rabbit antisera reacted with the over-expressed protein and against three small endogenous proteins. The antibody was affinity-purified using the peptide antigen immobilized on agarose beads. Anti-Dcr-2 antibody was raised in chicken using the KLH-conjugated peptide CKNADKSDRTYKTE. IgY was affinity-purified from egg yolk using peptide antigen immobilized on agarose beads. Anti-Drosha antibody was kindly provided by Greg Hannon [10].

Gel-filtration chromatography. 200 μl of S2 cell extract was separated by chromatography on a Superdex-200 HR 10/300 GL column (Amersham-Pharma) using a BioCad Sprint (PerSeptive Biosystems, Framingham, Massachusetts, United States) as described [75]. Protein from three-quarters of every other fraction was precipitated with 10% (v/v) trichloroacetic acid and 0.001% (w/v) deoxycholate and analyzed by Western blotting. The remainder of each fraction was analyzed for pre-miRNA processing activity.

Analysis of YFP reporter fluorescence and eye color using the white-IR transgene. Eye fluorescence and normal light pigments were taken with a Leica MZ-FLIII stereomicroscope equipped with a cooled color CCD-camera (Firecam, Leica, Wetzlar, Germany). The control animals expressing YFP without the miR-277 target sites contained a pBAC white-IR transgene.

The Rfam (http://www.sanger.ac.uk/Software/Rfam/mirna/index.shtml) accession numbers for the genes and gene products discussed in this paper are: aol1 (CG6671, FBgn0026611), aol2 (CG7439, FBgn0046812), armi (CG11513, FBgn0041146), aub (CG6137, FBgn000146), dcr-1 (CG4792, FBgn0039016), dcr-2 (CG6493, FBgn0034246), drosha (G8730, FBgn0031501), ltp (CG6866, FBgn0032515), pasha (CG1800, FBgn0039861), pri (CG6122, FBgn004872), r2d2 (CG7138, FBgn0031951), snpE (CG3158, FBgn003438), Stellate (FBgn003523), Su(Nc) (FBgn000382), vasa (CG3506, FBgn0003970), and white (CG2579, FBgn003996).

Accession Numbers

The Arabidopsis Information Resource (http://www.arabidopsis.org) accession numbers for the genes and gene products discussed in this paper are: DCL1 (AT1G01040) and HY1 (AT1G09700).

The Ensembl (http://www.ensembl.org/Rhomo__sapiens) accession numbers for the genes and gene products discussed in this paper are: c. elegans dgo4 (T28293.13) and dgo1 (K124H4.8), human DGCR8 (NSG00000128191), Ago2 (ENSG00000123590), Exportin5 (ENSG00000124571) and TRBP (ENSG00000139546), and mouse PRBP (ENSMUSG0000029051).

The FlyBase (http://flybase.bio.indiana.edu) accession numbers for the genes and gene products discussed in this paper are: ago1 (CG6671, FBgn0026611), ago2 (CG7439, FBgn0046812), armi (CG11513, FBgn0041146), aub (CG6137, FBgn000146), dcr-1 (CG4792, FBgn0039016), dcr-2 (CG6493, FBgn0034246), drosha (G8730, FBgn0031501), ltp (CG6866, FBgn0032515), pasha (CG1800, FBgn0039861), pri (CG6122, FBgn004872), r2d2 (CG7138, FBgn0031951), snpE (CG3158, FBgn003438), Stellate (FBgn003523), Su(Nc) (FBgn000382), vasa (CG3506, FBgn0003970), and white (CG2579, FBgn003996).

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Author contributions. KF, YT, TD, VVW, WET, and PDZ conceived the experiments. KF, YT, TD, VVW, DBP, CK, and WET designed the experiments. KF, YT, TD, VVW, DBP, CK, and WET performed the experiments. KF, YT, TD, VVW, DBP, CK, WET, and PDZ analyzed the data. KF, YT, TD, VVW, AMD, DBP, CK, WET, and PDZ contributed reagents/materials/analysis tools. KF, WET, YT, and PDZ wrote the paper.

References


