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Authors
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Mutations in SID2, a Novel Gene in Saccharomyces cerevisiae, Cause Synthetic Lethality With sic1 Deletion and May Cause a Defect During S Phase

Matthew D. Jacobson,*† Claudia X. Muñoz,† Kirstin S. Knox,† Beth E. Williams,† Lenette L. Lu,† Frederick R. Cross* and Elizabeth A. Vallen†

*The Rockefeller University, New York, New York 10021 and †Department of Biology, Swarthmore College, Swarthmore, Pennsylvania 19081

ABSTRACT

SIC1 encodes a nonessential B-type cyclin/CDK inhibitor that functions at the G1/S transition and the exit from mitosis. To understand more completely the regulation of these transitions, mutations causing synthetic lethality with sic1Δ were isolated. In this screen, we identified a novel gene, SID2, which encodes an essential protein that appears to be required for DNA replication or repair. sid2-1 sic1Δ strains and sid2-21 cln1Δ temperature-sensitive strains arrest preanaphase as large-budded cells with a single nucleus, a short spindle, and an ~2C DNA content. RAD9, which is necessary for the DNA damage checkpoint, is required for the preanaphase arrest of sid2-1 sic1Δ cells. Analysis of chromosomes in mutant sid2-21 cells by field inversion gel electrophoresis suggests the presence of replication forks and bubbles at the arrest. Deleting the two S phase cyclins, CLB5 and CLB6, substantially suppresses the sid2-1 sic1Δ inviability, while stabilizing Clb5 protein exacerbates the defects of sid2-1 sic1Δ cells. In synchronized sid2-1 mutant strains, the onset of replication appears normal, but completion of DNA synthesis is delayed. sid2-1 mutants are sensitive to hydroxyurea indicating that sid2-1 cells may suffer DNA damage that, when combined with additional insult, leads to a decrease in viability. Consistent with this hypothesis, sid2-1 rad9 cells are dead or very slow growing even when SIC1 is expressed.

P ASSAGE through the eukaryotic cell cycle is regulated by cyclin-dependent kinases (CDKs). CDKs are active when bound to cyclins and it appears that cyclins are responsible for much of the functional specificity of the cyclin-CDK complex. The activity of CDK complexes is regulated at the level of expression of CDKs and cyclins, as well as post-translationally by phosphorylation, regulated degradation, and CDK inhibitors. In the budding yeast Saccharomyces cerevisiae, Cdc28p is the main CDK involved in cell cycle control, forming a complex with both the G1 cyclins (Cln1-3) and the B-type cyclins (Clb1-6). The G1 cyclins act upstream of the events controlling the G1/S phase transition, including bud formation, microtubule organizing center duplication, and DNA replication (reviewed by Lew et al. 1997). One essential function of the G1 cyclins is the inactivation of the B-type cyclin-Cdc28 inhibitor, Sic1p, as sic1Δ deletion rescues strains containing a cln1Δ cln2Δ cln3Δ triple deletion that are otherwise inviable (Schneider et al. 1996).

As an inhibitor of Ccb-Cdc28 kinase activity, Sic1p appears to function to allow cells to exit mitosis as well as to prevent premature DNA replication (Schwob et al. 1994; Schneider et al. 1996). Sic1p proteolysis is dependent on its Cln-dependent phosphorylation (Schneider et al. 1996; Verma et al. 1997) and upon Cdc34p, an E2 ubiquitin-conjugating enzyme (Schwob et al. 1994). Inducing GAL-CLB5ΔDB expression advances DNA replication in sic1Δ, but not SIC1 cells, indicating that Sic1p has a function in regulating S phase entry (Schwob et al. 1994). Clb5p and Clb6p seem to have related, but not identical, roles in initiating DNA replication. clb5Δ cells initiate DNA replication normally, but take twice as long to complete DNA synthesis, upon the transcription factor Swi5p, and disappearing at the G1/S transition (Knapp et al. 1996). A decrease in Clb2p-Cdc28p activity is needed for passage into G1 and it appears that Sic1p assists in this process by inhibiting the CDK complex (Toyn et al. 1997). While cells can enter G1 with elevated levels of Clb2p, overexpressed Clb2ΔDBp (destruction box deleted) is lethal, causing cell cycle arrest in telophase (Surana et al. 1993). Clb2-Cdc28 kinase activity is also decreased by proteasome degradation of Clb2p after its ubiquitination by the anaphase-promoting complex (APC; Surana et al. 1993; Irniger et al. 1995).

At the G1/S transition, degradation of Sic1p releases inhibition of Clb5/6p-Cdc28p, which then induce DNA replication (Schwob et al. 1994; Schneider et al. 1996). Sic1p proteolysis is dependent on its Cln-dependent phosphorylation (Schneider et al. 1996; Verma et al. 1997) and upon Cdc34p, an E2 ubiquitin-conjugating enzyme (Schwob et al. 1994). Inducing GAL-CLB5ΔDB expression advances DNA replication in sic1Δ, but not SIC1 cells, indicating that Sic1p has a function in regulating S phase entry (Schwob et al. 1994). Clb5p and Clb6p seem to have related, but not identical, roles in initiating DNA replication. clb5Δ cells initiate DNA replication normally, but take twice as long to complete DNA synthesis (Epstein and Cross 1992; Kühne and Linder 1993). Cells deleted for clb6 display a normal onset and duration of replication. However, when clb5 and clb6 are both deleted, DNA synthesis is delayed, but the
duration of replication, once begun, is unaffected (Schwob and Nasmyth 1993). Recent evidence suggests that Cbl3p can activate early and late origins of replication while Cbl6p can activate only the early origins (Donaldson et al. 1998). This result agrees with the phenotypes of cbl5 and cbl6 single mutants. The phenotype of the double deletion can then be explained if the remaining Cbls (Clb1-4) can trigger both early and late origins to fire (Donaldson et al. 1998).

In addition to timing DNA replication, inhibition of Cbl5/6p-Cdc28p activity by Sic1p may function to regulate origin loading and the DNA replication machinery. Binding of the six-subunit origin recognition complex (ORC), the Mcm family (Mcm2-7), and Cdc6p is thought to make the origins competent for firing by Cbl5/6p-Cdc28p kinase activity (reviewed in Diffley 1996; Stillman 1996). Origin loading is inhibited by CDK activity and this is thought to be the basis for a mechanism that allows replication to occur once per cell cycle (Dahmann et al. 1995). Cdc6p appears to recruit Mcm binding to the origins. In the presence, but not in the absence of SIC1, late G1 expression of Cdc6p (under the control of the HO promoter) can promote Mcm binding (Tanaka et al. 1997). This suggests that Sic1-induced delay of Clb-Cdc28 activity allows proper origin binding of competence factors in preparation for DNA replication. Cbl-Cdc28 kinase activity and Sic1p also affect DNA replication in a Cdc6- and ORC-independent fashion, suggesting that the kinase may also have direct effects on enzymes required for DNA synthesis (Duncker et al. 1999). One possibility is that the Cbl-Cdc28 kinase regulates the association of DNA polymerase-primase (polo) to chromatin (Desdouets et al. 1998).

SIC1 is not an essential gene, but sic1 cells show a high frequency of chromosome loss and breakage (Nugroho and Mendenhall 1994). Several genetic backgrounds make SIC1 essential, including DBF2, GAL-CLB2, cld1Δ/hct1Δ, cdc23-1, and rsil-1 (apc2; Schwab et al. 1997; Toyn et al. 1997; Kramer et al. 1998). Overexpression of Sic1p is able to rescue cdc5, cdc14-1, cdc15, and cdc20-1 strains (Schwab et al. 1997; Toyn et al. 1997; Jaspersen et al. 1998). All of these genetic interactions appear to be related to Sic1’s function at the exit from mitosis. Cdc23p and Apc2p are members of the APC (Zachariae et al. 1998b) while Cdc20p and Cdh1p/ Hct1p seem to function as APC activators (Schwarb et al. 1997; Visintin et al. 1997). DBF2, cdc6, cdc5, cdc14, and cdc15 all have terminal arrest phenotypes late in mitosis (Byers and Goeletsh 1973; Pringle and Hartwell 1981; Johnston et al. 1990; Kitada et al. 1993) and may activate the APC or dephosphorylate Cdc28 substrates or regulators (Jaspersen et al. 1998; Visintin et al. 1998). Taken together, these data indicate that SIC1 plays an important role in late mitosis. If SIC1 also has a significant role in regulating DNA replication, it is possible that genes exist which, when mutated in combination with sic1Δ, disrupt the normal regulated process of DNA replication sufficiently to render the cells inviable. To identify such genes, as well as other genes playing roles in the exit from mitosis, we screened for mutations causing synthetic lethality with sic1Δ. Here we report on the discovery of a novel gene, SIC2, which appears to play a role in DNA replication.

MATERIALS AND METHODS

**Yeast strains and media:** YE-dextrose (YPD), YE-galactose (YPGal), and synthetic complete (SC) minimal media were made by standard techniques (Ausubel et al. 1987). Hydroxyurea and α-factor (both from Sigma Chemical, St. Louis) were used at 0.2 and 0.1 μM, respectively. The strains and plasmids used in this study are listed in Tables 1 and 2, respectively. All yeast strains are isogenic with BP264-15D (replication origin recognition complex (ORC), the Mcm family (Mcm2-7), and Cdc6p is thought to make the origins competent for firing by Cbl5/6p-Cdc28p kinase activity (reviewed in Diffley 1996; Stillman 1996). Origin loading is inhibited by CDK activity and this is thought to be the basis for a mechanism that allows replication to occur once per cell cycle (Dahmann et al. 1995). Cdc6p appears to recruit Mcm binding to the origins. In the presence, but not in the absence of SIC1, late G1 expression of Cdc6p (under the control of the HO promoter) can promote Mcm binding (Tanaka et al. 1997). This suggests that Sic1-induced delay of Clb-Cdc28 activity allows proper origin binding of competence factors in preparation for DNA replication. Cbl-Cdc28 kinase activity and Sic1p also affect DNA replication in a Cdc6- and ORC-independent fashion, suggesting that the kinase may also have direct effects on enzymes required for DNA synthesis (Duncker et al. 1999). One possibility is that the Cbl-Cdc28 kinase regulates the association of DNA polymerase-primase (polo) to chromatin (Desdouets et al. 1998).

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**TABLE 1**

<table>
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<tr>
<th>Strain</th>
<th>Relevant genotype</th>
<th>Source</th>
</tr>
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<tbody>
<tr>
<td>KK1</td>
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<td>MJ65</td>
</tr>
<tr>
<td>KK11</td>
<td>MATα SID2 sic1::TRP1 GAL1-SIC1</td>
<td>KK1 × MJ163</td>
</tr>
<tr>
<td>KK17</td>
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<td>KK1 × MJ163</td>
</tr>
<tr>
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<td>MATα SID2 sic1::TRP1 GAL1-SIC1 rad9::LEU2</td>
<td>KK1 × MJ163</td>
</tr>
<tr>
<td>KK29</td>
<td>MATα sid2-1 sic1::TRP1 GAL1-SIC1 rad9::LEU2</td>
<td>KK1 × MJ163</td>
</tr>
<tr>
<td>L40</td>
<td>lexA operator::HIS3 lexA operator::lacZ trp1</td>
<td>HOLLENBERG et al. (1995) RHEE et al. (2000)</td>
</tr>
<tr>
<td>LY623</td>
<td>MATα sic1::TRP1 GAL1-SIC1::URA3</td>
<td>K2944 (OEHLEN and CROSS 1994)</td>
</tr>
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<td>MATα adc15::sid1::TRP1</td>
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</tr>
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<td>MATα HIS2 his3</td>
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<td>MATα HIS2 his3 sid2::LEU2 pSU3[SID2-RS416]</td>
<td>S7-4A (L. H. Johnston)</td>
</tr>
<tr>
<td>LY1036</td>
<td>MATα HIS2 his3 SID2</td>
<td>S7-4A (L. H. Johnston)</td>
</tr>
<tr>
<td>LY1037</td>
<td>MATα HIS2 his3 sid2-21</td>
<td>S7-4A (L. H. Johnston)</td>
</tr>
<tr>
<td>LY1118</td>
<td>MATα sid2-1</td>
<td>S7-4A (L. H. Johnston)</td>
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<td>MJ55</td>
<td>MATα sic1::TRP1 GAL1-SIC1::URA3</td>
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<td>MATα sic1::TRP1 GAL1-SIC1::URA3</td>
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<td>MJ160</td>
<td>MATα sid2-1 sic1::TRP1 GAL1-SIC1::URA3</td>
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<td>MJ163</td>
<td>MATα sid2-1 sic1::TRP1 GAL1-SIC1::URA3</td>
<td>S7-4A (L. H. Johnston)</td>
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<td>MJ193</td>
<td>MATα sid2-1 sic1::TRP1 GAL1-SIC1::URA3</td>
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<td>MATα cdh1::LEU2 sic1::TRP1 GAL1-SIC1::URA3</td>
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<td>MATα sbd2::LEU2 sic1::TRP1 GAL1-SIC1::URA3</td>
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<td>MATα sid2-1 CLB2Δ8::sic1::TRP1 GAL1-SIC1::URA3</td>
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<td>MATα SID2 sic1::TRP1 GAL1-SIC1 CLB9Δ8::sic1::TRP1 GAL1-SIC1::URA3</td>
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<td>MJ317</td>
<td>MATα sid2-1 sic1::TRP1 GAL1-SIC1 CLB9Δ8::sic1::TRP1 GAL1-SIC1::URA3</td>
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<td>MJ319</td>
<td>MATα SID2 sic1::TRP1 GAL1-SIC1 CLB5ΔD86::sic1::TRP1 GAL1-SIC1::URA3</td>
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<td>MJ321</td>
<td>MATα sid2-1 sic1::TRP1 GAL1-SIC1::URA3 sid2-1 CLB5ΔD86::sic1::TRP1 GAL1-SIC1::URA3</td>
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<td>MJ322</td>
<td>MATα sid2-1 sic1::TRP1 GAL1-SIC1::URA3</td>
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<td>MJ323</td>
<td>MATα sid2-1 sic1::TRP1 GAL1-SIC1::URA3</td>
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<tr>
<td>MJx21-4D</td>
<td>MATα dbh2::URA3 GAL1-SIC1::URA3</td>
<td>S7-4A (L. H. Johnston)</td>
</tr>
</tbody>
</table>

All strains are ade1 trp1-1 ura3 leu2-3,112 his2 bar1 and are from this study unless otherwise noted.

analysis, MJ257 was crossed to a SID2 strain (MJ58). The diploid was sporulated and the tetrads were dissected for analysis. If the sid2-1 mutation was not linked to YJR046w, approximately half of the Leu+ spores should have had the Sid− phenotype because the mutation would have been segregating independently of the LEU2 integration. None of the spores (54 spores analyzed) were Sid−, indicating that the sid2-1 mutation was linked to YJR046w. In addition, when MJ257 was crossed to sid2-1 strains, all Leu− spores were Sid− and all Leu+ spores were Sid+. (47 spores analyzed), indicating tight linkage between the integrated DNA and the SID2 locus. SID2 was deleted in a diploid heterozygous for sid1α and GAL1-SIC1 using pMJ07, which was derived from pMJ01 in the following way. The XhoI polylinker site in pMJ01 was removed with a SpeI/Nael digest. The 5′ overhanging ends of the digested plasmid were blunted using Klenow enzyme and then ligated, to form pMJ03. pMJ03 was then digested with XhoI, liberating a 970-bp fragment internal to SID2, and the ends were blunted with Klenow enzyme. A 3.5-kb fragment containing the LEU2 and Kan' genes from pJA51-ΔP digested with Smal (CROSS 1997) was ligated to the digested MJ03 to form MJ07. pMJ07 was digested with HindIII and the resulting 5-kb fragment was gel purified and used to disrupt SID2 in a diploid by homologous recombination. A diploid containing the deletion (confirmed by Southern blot) was sporulated and tetrads were dissected.

Construction of the temperature-sensitive **SID2** allele, sid2-2H: SID2-HIS3 (pSH6) and SID2-URA3 (pSU3) plasmids were made by gap repair by first isolating a 5.6-kb fragment (SalI to DraI) containing all of SID2 and flanking vector sequences.
from pMJ02 and 3-kb Pvu vector fragments from both pRS413 and pRS416. The pMJ02 SID2 fragment and either the pRS413 or pRS416 fragment were cotransformed into LY194 and the resultant plasmids were isolated. pSH6 was then mutagenized with hydroxylamine according to standard procedures (Rose et al. 1990).

Haploid strains containing pSU3 (SID2-URA3) were deleted for SID2 using pMJ07 as described above. The sid2::LEU2 deletion was confirmed in the resulting Leu<sup>+</sup> FOA<sup>−</sup> strains by Southern blot analysis. One such strain, LY1023, was transformed with pSH6 (SID2-HIS3) and became FOA<sup>−</sup> as expected. LY1023 was then transformed with hydroxylamine-mutagenized pSH6 and plated on SC Dex-His at room temperature (~200 colonies per plate). The colonies were replica plated to SC Dex-His and SC Dex + FOA at both room temperature and 37°C and then screened for mutants that were dead only on SC Dex + FOA. The plasmids were recovered from these strains and transformed back into LY1023 to verify the phenotype. Five sid2-ts plasmids were isolated from ~7700 colonies screened with a 1% frequency of sid2 null mutations (FOA<sup>+</sup> at room temperature and 37°C).

The 3.5-kb SpeI to Sall fragments containing the sid2-ts alleles were isolated from the five plasmids and cloned into pRS406 digested with Xhol and SpeI. These new sid2-ts integrating plasmids were digested with Xhol (which cuts uniquely in SID2) and integrated by homologous recombination into LY194. Purified Ura<sup>+</sup> transforms were patched onto YPD at room temperature and then streaked on SC Dex + FOA at 37°C. The plasmids were recovered from these strains and transformed back into LY1037 to confirm the phenotype. Five sid2-ts plasmids were isolated from ~7700 colonies screened with a 1% frequency of sid2 null mutations (FOA<sup>+</sup> at room temperature and 37°C).

Phenotypic analysis of sid2-1 sic1 and sid2-21 strains: SID2 and sid2-1 strains (both sid2 GAL1-SIC1) were grown overnight to early log phase in liquid YPGal media. The cultures were then split and dextrose was added to one-half of each to a final concentration of 2%. YPD cultures of sid2-21 and SID2 strains were grown overnight at 25°C to early log phase and then shifted to 37°C. For both experiments, samples were removed every 24 hr and processed for FACS analysis, cell counting, or immunofluorescence staining as described below. Below the synchronization experiments, early log phase cultures of SID2, sid2-21, SID2 sic1 GAL1-SIC1, and sid2-21 sic1 GAL1-SIC1 were grown in YPGal at 30°C. α-factor was added and incubation continued for 3 hr. Cells were centrifuged, washed in YP lacking sugar, and resuspended in fresh 30°C YPD. Samples were removed at 12-min intervals.

**TABLE 2**

<table>
<thead>
<tr>
<th>Name</th>
<th>Vector</th>
<th>Relevant genes</th>
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<tbody>
<tr>
<td>pMJ01</td>
<td>RS405</td>
<td>SID2, LEU2</td>
<td>This study</td>
</tr>
<tr>
<td>pMJ02</td>
<td>RS415</td>
<td>SID2, LEU2</td>
<td>This study</td>
</tr>
<tr>
<td>pMJ03</td>
<td>RS405</td>
<td>SID2, LEU2 (Xhol in polynlinker removed)</td>
<td>This study</td>
</tr>
<tr>
<td>pMJ07</td>
<td>RS405</td>
<td>sid2::LEU2 Kan&lt;sup&gt;+&lt;/sup&gt;</td>
<td>This study</td>
</tr>
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<td>pSC1</td>
<td>RS315</td>
<td>SIC1, LEU2</td>
<td>M. Tyers</td>
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<td>pSH6</td>
<td>RS413</td>
<td>SID2, HIS3</td>
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<tr>
<td>pSU3</td>
<td>RS416</td>
<td>SID2, URA3</td>
<td>This study</td>
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</tbody>
</table>

were used to amplify the protein A-his<sup>5</sup> fragment for C-terminal addition of protein A to Sid2. 046-PROTA 5', GGATA AAAACAGATTTTCTAAGCTGTGGTGGCAAATCCAAATCTCA AACAACACAGATGGTGAAGCTCTAAAACATTAT-046-HIS3', GGATCATCAGATGACAGCTTCAAAATACCGAC CGTATGATACAGATCGTACGCGATGTAAGCTTT where the underlined sequences correspond to those from SID2. Twenty-five cycles of PCR consisting of 1 min at 95°C, 1 min at 55°C, and 4 min (+5-sec increase/cycle) at 72°C were performed. The PCR products were transformed into his3/ his3 diploid cells (LY915) and His<sup>+</sup> transformants were selected. Homologous recombination resulted in SID2::Proa fusions linked to his3<sup>+</sup>. Putative protein A-tagged strains were analyzed by Western and Southern blotting to verify tagging of the Sid2 protein.

**Construction of lex-A-GAL1-SID2 fusions and “one-hybrid” assay:** The SID2 gene was amplified with forward primer 5'-AAA GAGATGCAATACCCGGGACCTTTATGATTGGCCAACGG TAAATG-3' and reverse primer 5' -TCGGCGGAATTCGCTTGC GATACAACTTGTTTGGTGTTTATG-3' using the Expand High Fidelity PCR system (Roche, Indianapolis). The underlined sequences correspond to those from SID2 and the italicized sequences correspond to sequences in the pNIA plasmid. Thirty-three cycles of PCR each consisting of of 1 min at 94°C, 1 min at 50°C, and 2 min at 68°C were performed. The PCR fragment was recombined into plasmid pNIA (Rhee et al. 2000) by cotransformation into yeast. Plasmids were recovered from yeast (Hoffman and Winston 1987), electroporated into Escherichia coli, and analyzed by restriction analysis. Six independently derived NIA-SID2 plasmids were transformed into strain L40 (Rhee et al. 2000) and liquid β-galactosidase assays were performed on log phase cultures grown under selective conditions as described (Ausubel et al. 1987).

**Yeast fractionation:** Fractionation was performed (Rout and Kilmartin 1998) using the modifications for S. cerevisiae described with a 1-liter culture of Wickerham’s media grown overnight to an optical density (660 nm) of 0.8. The volumes loaded for Western blot analysis were adjusted to compensate for varying total volumes of each collected fraction.

**Phenotypic analysis of sid2-1 sic1 and sid2-21 strains:** SID2 and sid2-1 strains (both sid2 GAL1-SIC1) were grown overnight to early log phase in liquid YPGal media. The cultures were then split and dextrose was added to one-half of each to a final concentration of 2%. YPD cultures of sid2-21 and SID2 strains were grown overnight at 25°C to early log phase and then shifted to 37°C. For both experiments, samples were removed every 24 hr and processed for FACS analysis, cell counting, or immunofluorescence staining as described below. For the synchronization experiments, early log phase cultures of SID2, sid2-21, SID2 sic1 GAL1-SIC1, and sid2-21 sic1 GAL1-SIC1 were grown in YPGal at 30°C. α-factor was added and incubation continued for 3 hr. Cells were centrifuged, washed in YP lacking sugar, and resuspended in fresh 30°C YPD. Samples were removed at 12-min intervals.

**FACS analysis and cell counting:** Flow cytometric DNA quantification was performed as described elsewhere (Epstein and Cross 1992). Growth curve samples were fixed with 3 ml of 0.74% formaldehyde in 1× PBS. The samples were sonicated for 12 sec and cell number was analyzed using a Coulter counter. Microscopic analysis was used to determine the percentage of cells that were unbudded, small budded, or large budded. At each time point, at least 200 cells were counted. Small-budded cells were those where the daughter bud was less than two-thirds the size of the mother bud. Large-budded cells had a daughter bud greater than two-thirds the size of the mother bud.

**Field inversion gel electrophoresis assay:** Yeast strains 1036 (SID2) and 1037 (sid2-21) were grown to early log phase in YPD at 23°C. Samples of the wild type and mutant were removed for...
processing, the cultures were shifted to 37°C, and samples were then removed at 24 hr intervals. For the hydroxyurea-treated control sample, hydroxyurea was added directly to an aliquot of the log phase culture of wild-type cells (final concentration, 0.2 M) and incubation continued for 3 hr at 30°C. Chromosomal DNA samples were prepared in agarose plugs as described (Schwartz and Cantor 1984; Ross et al. 1990). Samples containing equivalent OD_{600} units of cells were applied to 1% agarose gel, electrophoresed in 0.5× Tris-borate-EDTA buffer at 4–8°C at 8.3 V/cm, stained with ethidium bromide overnight, and then destained for 1 hr. Field inversion was controlled by a PC500 SwitchBack pulse controller (Hoefer, Amersham Pharmacia Biotech, Piscataway, NJ) with a run time of 32 hr, a pulse time of 1–50 sec and an F/R ratio of 3:0:1.

Immunofluorescence staining: Immunofluorescence microscopy was done essentially as described previously (Wente et al. 1992). Tubulin was visualized using anti-tubulin antibody (Wente et al. 1992; 1:200 dilution) followed by Cy-3 donkey conjugated anti-rat IgG (Jackson ImmunoResearch Laboratories, West Grove, PA). The fluorescent DNA-specific dye 4',6-diamidino-2-phenylindole (DAPI) was used to visualize yeast nuclei.

Immunoprecipitation and detection of HA-tagged proteins: The immunoprecipitation protocol is based on methods described previously (Levine et al. 1996). Yeast cultures (100 ml) were grown overnight to an optical density (600 nm) of 1.0. Cells were collected and washed in TNN buffer (50 mM Tris pH 7.5, 250 mM NaCl, 5 mM EDTA, 10% glycerol, 0.1% Nonidet P-40). TNN extraction buffer (TNN + 5% aprotinin (Sigma), 0.1 mM phenylmethylsulfonyl fluoride, 10 μg/ml leupeptin, 10 μg/ml pepstatin, 10 mM NaPPi (pH 7.4), 10 mM NaF) was used for cell breaking, antibody incubation, and immunoprecipitation with the protein A-agarose slurry. The extract was incubated for 1 hr on ice with 1 μl of the monoclonal HA11 antibody (ascitis; Babco). Following incubation with the antibody, the extract was added to 30 μl of a protein A-agarose slurry (Sigma) prewashed with TNN and rotated at 4°C for 1 hr.

SDS-polyacrylamide gel electrophoresis (10%) and transfer to Immobilon were done as previously described (Cross and Blake 1999). Following the transfer, the immunoblots were blocked overnight [PBS with 0.5% Nonidet P-40, 0.1% Tween 20, 0.5% BSA, and 15% milk (Carnation)]. The blot was incubated with antibodies (1.5 hr for the primary, 1 hr for the secondary) in PBS-Tween 20 (0.2%) with 1% milk at room temperature. The primary antibody, polyclonal rabbit anti-HA (Covance Research Products, Richmond, CA), was diluted 1:7500. The secondary antibody was a 1:1500 dilution of polyclonal donkey anti-rabbit conjugated to horseradish peroxidase (Amerham). The samples were washed three times for 10 min each with PBS-Tween 20 following each antibody incubation. The proteins were then detected using an enhanced chemiluminescence kit (Amerham).

Other Western blots were processed as described above except for the following modifications. The blots were blocked for 1 hr at room temperature in PBS-Tween 20 with 2.5% milk and incubated with the antibodies in PBS-Tween 20 containing 5% milk. A 1:1000 dilution of rabbit anti-mouse IgG (Organon Teknika, Durham, NC) was used to detect protein A tags. Mouse monoclonal anti-Nop1 (Aris and Blobel 1988) was diluted 1:2000 and mouse monoclonal anti-PGK (Molecular Probes, Eugene, OR) was diluted 1:10,000. The secondary antibody was a 1:1000 dilution of polyclonal donkey anti-rabbit (sheep anti-mouse for Nop1 and PGK) conjugated to horseradish peroxidase (Amerham).

RESULTS

Isolation of mutants synthetically lethal with sic1 deletion: To identify factors that assist SIC1 at the G1/S transition or at the exit from mitosis, we isolated mutations that caused synthetic lethality with sic1Δ. sic1Δ GAL1-SIC1 strains (LY623 and MJ65) were mutagenized and screened for mutants alive on YPGal (SIC1 expressed) and dead onYPD (SIC1 repressed). Approximately 28,000 colonies were screened by replica plating and 21 recessive mutants were isolated. The mutants were named SIC2 for SIC1 Indispensable.

By complementation testing, the following groups were established: sid1 (seven alleles), sid2 (two alleles), sid3/dbf2 (six alleles), and sid4/cdc15 (one allele). The remaining six mutants do not fall into the four complementation groups described above and define at least two more complementation groups. They remain unsorted because of difficulties with backcrossing. There appears to have been spontaneous diploidization of many of the mutants, resulting in minimal spore viability following tetrad dissection after crosses to wild-type haploid strains. Attempts to sporulate the diploidized strains after transformation with MAT containing plasmids were unsuccessful. sid1 has yet to be cloned, though two LEU2 CEN libraries have been thoroughly screened for rescue plasmids (39,000 transformants). Preliminary analysis suggests that sid1 sic1Δ strains arrest as large-budded cells with segregated nuclei (data not shown). sid3 sic1Δ mutants failed to complement a dbf2Δ sic1Δ GAL1-SIC1 strain (LY699) on YPD and sid3 was meiotically linked to dbf2 (MJX21D) in tetrad analysis. The sid4 sic1Δ mutant failed to complement a cdc15-2 sic1Δ strain (LY677). Linkage could not be established, however, as the sid4 mutant had spontaneously diploidized. Although cdh1Δ sic1Δ spores are inviable (Schwab et al. 1997), no cdh1 mutants resulted from this screen as determined by complementation testing to MJ249 and MJ242. cdh1Δ sic1Δ spores were isolated in our strain background using GAL1-SIC1 to suppress the lethality. cdh1Δ sic1Δ spores that did not contain GAL1-SIC1 were inviable as previously reported. cdh1Δ sic1Δ GAL1-SIC1 strains were able to grow when replica plated to YP-dextrose, though they clearly grew more slowly than sic1Δ GAL1-SIC1 strains (data not shown). Thus the very low level of expression from GAL1-SIC1 on glucose is probably sufficient to partially rescue cdh1Δ sic1Δ GAL1-SIC1 strains on glucose medium, which may account for our failure to isolate cdh1 mutations in our screen. The isolated sid1 mutants were all found to complement cdc5 and cdc14 strains.

SIC2 is YJR046w, a novel gene: To clone SIC2, a LEU2 CEN4 library was screened for plasmids that could rescued the lethality of sid2-1 sic1Δ GAL1-SIC1 cells on YPD. Four plasmids containing the yeast ORF YJR046w/TAH11 and flanking regions were isolated after screening 8000 transformants. An insert containing only YJR046w intact was subcloned into RS415 and the resulting plasmid (pMJ02) was able to rescue the lethality of sid2-1 sic1Δ GAL1-SIC1 cells on YPD (Figure 1A). LEU2 was integrated adjacent to YJR046w in a sid2-1 strain and was found to be meiotically linked to SIC2 (Materials and Methods). SIC2 encodes...
a 604-amino-acid protein lacking significant homology to any known genes. Since SID2 was known to be essential in wild-type cells (Huang et al. 1997), a sid2Δ GAL1-SIC1 strain was constructed to determine if the sid2 null mutation could be rescued by elevated Sic1 levels. SID2 was deleted in a diploid heterozygous for GAL1-SIC1 and sic1Δ using a construct that removed 1 kb internal to SID2 and inserted a 3.5-kb fragment containing LEU2-Kan’ (Figure 1C). The diploid was sporulated and the tetrads were dissected on galactose-containing media. All viable spores were Leu’; the spores predicted to contain sid2::LEU2 were inviable even when they were predicted to contain GAL1-SIC1. Therefore, overexpression of SIC1 does not suppress the lethality caused by deletion of SID2. Most of the further analysis of SID2 was performed using sid2-1 strains. The sid2-1 mutation was backcrossed from the original mutagenized strain into the sic1Δ GAL1-SIC1 background at least four times before further analysis.

SID2 on a centromere-based plasmid completely rescued the lack of growth of the sid2-1 sic1Δ cells (Figure 1A). Similarly, GAL1-SIC1 overexpression permitted growth of sid2-1 sic1Δ strains on YPGal that was comparable to wild type (Figure 1A). To demonstrate that growth of sid2-1 sic1Δ strains on YPGal was dependent on the presence of GAL1-SIC1, we dissected diploids heterozygous for sid2-1, sic1Δ, and GAL1-SIC1 on YPGal. SID2::LEU2 was also segregating in the cross, allowing unambiguous determination of sid2-1 spores. Dissection of 65 tetrads on YPGal gave 25 spores that could unequivocally be predicted to be sid2-1 sic1Δ and lacking GAL1-SIC1; all were dead. In contrast, the viability of SID2 sic1Δ cells lacking GAL1-SIC1 was 86% (n = 29).

The screen that isolated sid2-1 identified mutants that were viable in the presence of high levels of SIC1 and inviable in the absence of SIC1. To determine whether sid2-1 mutant cells required the high levels of SIC1 expressed from the GAL1 promoter throughout the cell cycle, we assayed the growth of sid2-1 cells in the presence of lower levels of SIC1. In contrast to the complete suppression by GAL1-SIC1, sid2-1 sic1Δ strains were only partially rescued by SIC1 on a centromere-based plasmid when SIC1 was expressed under the control of its own promoter (Figure 1A). However, a more complete rescue of sid2-1 strains by endogenous SIC1 was observed in backcrosses where the wild-type SIC1 gene was segregating against sic1Δ. When diploids heterozygous for sid2-1 and sic1Δ were sporulated and tetrads were dissected, colonies that were sid2-1 SIC1 were similar in size to those that were SID2 SIC1 (data not shown). When sid2-1 SIC1 spores were analyzed, they gave plating efficiencies more similar to wild-type SID2 SIC1 strains (Figure 1B), although a slight decrease in both the number of colony forming units and colony size could still be observed in the sid2-1 SIC1 strain. The observed difference between the ability of plasmid and chromosomal SIC1 to rescue may be due to a lack of regulatory regions in the SIC1-containing plasmid. The suppression of sid2-1 by wild-type levels of SIC1 demonstrates that overexpression of SIC1 is not absolutely required for the viability of sid2-1 mutant cells. Although the sid2-1 SIC1 mutant cells appear to grow fairly similarly to wild type, they do have an increase in the number of cells with a 2C DNA content and large buds compared to SID2 SIC1 cells (Figure 7, E and F). Based on the other phenotypes of sid2 mutants, it is likely that this phenotype is due to a defect in DNA replication or induction of a DNA damage checkpoint. It is less likely that the sid2 mutant cells replicate their DNA prematurely compared to wild type because sid2 mutant cells are actually delayed...
in DNA replication compared to wild-type cells (see below).

**Sid2p, while predominantly cytoplasmic, has a functional nuclear import signal:** Determining the timing of Sid2p expression or its intracellular localization might aid our understanding of how and when Sid2p functions. To detect Sid2p, we tagged the genomic locus of *SID2* with protein A and detected it by Western blot. *SID2-PrA* strains do not show a growth defect and have a wild-type FACS profile (data not shown). In addition, *SID2-PrA* *sic1Δ* strains are viable. This indicates that the protein A tag does not interfere with Sid2p function. A strain containing the tagged *SID2* gene was arrested with α-factor and released into YPD. Protein extracts were made at 12-min intervals following the α-factor release and Sid2p levels were found to remain constant throughout the cell cycle (data not shown).

We could not detect Sid2-PrA by immunofluorescent staining of either logarithmically growing or hydroxyurea (HU)-arrested cells, perhaps because the level of expression is low or the localization is diffuse. Following fractionation of the Sid2-protein A-containing strain, Sid2p protein was visualized by Western blot and found to be predominantly cytoplasmic, although a small amount of nuclear Sid2p could be detected (Figure 2A). Interestingly, analysis of Sid2p’s localization using a one-hybrid assay (Rhee et al. 2000) suggests that Sid2p has a functional nuclear localization signal (NLS; Figure 2B). A fusion protein containing a modified *lexA* DNA-binding domain, the *GAL4* transcriptional activation domain, and Sid2p (NIASID2) could enter the nucleus and activate transcription from a *lexA*-operator-driven *lacZ* reporter gene. In contrast, a control fusion containing the cytoplasmic protein VirE2, which is of similar size to Sid2p, could not activate transcription from the reporter gene (NIAE2, Figure 2B; Rhee et al. 2000). Levels of transcriptional activation from the Sid2p-containing construct were lower than that from a control construct containing the NLS from *SV40* T antigen (NEAE2). Taken together with the fractionation experiments, these data suggest that Sid2p has a functional NLS, although it may be weak or subject to regulation.

**sid2-1 sic1Δ and sid2-21 cells have a preanaphase arrest:** To characterize the effect of the *sid2-1* mutation, we analyzed the morphology of *sid2-1* and *SID2* cells (both *sic1Δ GAL1-SIC1*) in the absence of *SIC1* expression by shifting cultures from YPGal (*SIC1* expressed) to YPD (*SIC1* repressed). *sid2-1 sic1Δ* cells slowed proliferation and then arrested 6 hr after repression of *GAL1-SIC1*, showing only minimal increases in cell number at later time points (Figure 3A). There was no decrease in viability up to 5 hr after the shift to dextrose-containing media and a slight decrease in viability (less than fourfold) by 10 hr after the shift (data not shown). *sid2-1 sic1Δ* cells accumulated with large buds at the arrest point (Figure 3, B and D). Repression of *SIC1* slightly decreased the number of unbudded cells in the *SID2* strain but otherwise had little effect on the distribution of cell morphologies (Figure 3B).

Similarly, we compared the morphology of wild-type *SID2* cells and cells containing a temperature-sensitive allele, *sid2-21*, after incubation at the nonpermissive temperature. *sid2-21* cells began to die by 3 hr after shift to 37°C (Figure 4A). After 4 hr of incubation at 37°C, the *sid2-21*
cells accumulated with large buds similar to the sid2-1 sic1Δ-arrested cells (Figure 4, B and D). The distribution of cell morphologies of SID2 cells, in contrast, was unaffected by the temperature shift (Figure 4B).

The arrest of sid2-1 sic1Δ and sid2-21 cells was further examined using FACS to analyze DNA content. By 6 hr after repression of GAL1-SIC1, the DNA content of SID2 cells was predominately 2C, though a small 1C peak was also observed (Figure 3C). Cells deleted for sic1 have a short G1 phase probably due to the lack of S phase cyclin/CDK (Clb5/Clb6p-Cdc28p) inhibition (Schwob et al. 1994). The DNA content of the mutant sid2-1 sic1Δ cells also shifted primarily to an ~2C peak. However, in contrast to the SID2 sic1Δ cells, the sid2-1 sic1Δ population at 6 hr after shift to YPD had a less distinct 1C peak, and the 2C peak was much broader, having a shoulder of cells with DNA content between 1C and 2C (Figure 3C). These data indicate that, although the mutant cells were able to replicate at least most of their DNA in the absence of SIC1 expression, they may have some defect associated with DNA synthesis.

The DNA contents of the SID2 and sid2-21 populations of cells were similar at 25°, with cells approximately equally distributed between two distinct peaks at 1C and 2C (Figure 4C). For the SID2 cells, this profile remained constant after the temperature shift to 37°. In contrast, 2 hr after the shift to the nonpermissive temperature, the sid2-21 cells accumulated with a DNA content intermediate between the 1C and 2C peaks. By 4 hr at the nonpermissive temperature, the DNA content of the sid2-21 cells shifted to a broad, ~2C peak (Figure 4C). These data indicate that, like the sid2-1 sic1Δ cells, the sid2-21 mutant cells appear to replicate most or all of their DNA under nonpermissive conditions. However, the accumulation of cells in S phase at 2 hr suggests that sid2 mutants may have a defect in DNA replication (see also below).
To characterize the defect in the *sid2* mutants more completely, *sid2-1 sic1Δ, SID2 sic1Δ, sid2-21*, and *SID2* cells were stained with DAPI and tubulin was visualized by indirect immunofluorescence. In contrast to the *SID2 sic1Δ* and *SID2* cells that were at various cell cycle stages, the *sid2-1 sic1Δ* and *sid2-21*-arrested cells appeared to be pre-anaphase with a single nucleus and a short spindle (Figures 3D and 4D). The arrest morphology of *sid2 sic1Δ* and *sid2-21* cells suggests that, unlike other mutations that are lethal in combination with *sic1Δ*, the primary defect of the *sid2* mutants is not in the reduction of Clb2p-CDK activity. Mutants that fail to inactivate Clb2p-CDK activity arrest primarily in telophase with elongated spindles and DNA segregated between the mother and bud (Surana et al. 1993). The arrest phenotype demonstrated by the *sid2-1 sic1Δ* and *sid2-21* cells has some similarities to phenotypes demonstrated by mutants that affect DNA replication or APC activation. Of these, the slow S phase observed in *sid2-1 sic1Δ* and *sid2-21* arrested cells appeared to be pre-anaphase with a single nucleus and a short spindle (Figures 3D and 4D). The arrest morphology of *sid2 sic1Δ* and *sid2-21* cells suggests that, unlike other mutations that are lethal in combination with *sic1Δ*, the primary defect of the *sid2* mutants is not in the reduction of Clb2p-CDK activity. Mutants that fail to inactivate Clb2p-CDK activity arrest primarily in telophase with elongated spindles and DNA segregated between the mother and bud (Surana et al. 1993). The arrest phenotype demonstrated by the *sid2-1 sic1Δ* and *sid2-21* cells has some similarities to phenotypes demonstrated by mutants that affect DNA replication or APC activation. Of these, the slow S phase observed in the *sid2-21* mutant strains is most consistent with a defect in DNA replication.

**Both S and M phase B-type cyclins are only slightly stabilized in sid2-1 mutants:** One possibility, based on the morphology of *sid2-1 sic1Δ* cells, was that *sid2-1* affected APC activity. It has previously been demonstrated that a
number of mutants that affect APC activity are lethal in combination with deletion of sic1 (ToyN et al. 1997; Schwab et al. 1997; Kramer et al. 1998). Mutants that fail to activate the APC have defects in the degradation of Clb2p (Irniger et al. 1995; Zachariae et al. 1996; Kramer et al. 1998). In addition, Clb5p degradation appears, at least in part, also to be regulated by the APC (Irniger and Nasmyth 1997; Shirayama et al. 1999). Failure to degrade the B-type cyclins (caused by a mutation in an APC component), coupled with lack of inhibition of the CDK kinase (caused by deletion of sic1), appears to result in levels of CDK kinase that are too high to allow progression through mitosis. We therefore analyzed Clb5p and Clb2p stability in sid2-1 sic1Δ cells to determine whether increased B-type cyclin levels could contribute to the observed phenotypes.

An asynchronous culture of a genomically tagged CLB5ΔHA strain was treated with α-factor, which blocks CLB5 expression (Einstein 1992). Clb5p turnover was examined by following protein levels during the arrest. A strain in which Clb5-HAp’s destruction box was removed was used as a positive control (CLB5ΔDBΔHA). The levels of Clb5-HAp resulting from the deletion of the destruction box do not affect the viability of cells even in the absence of sic1 (Figure 6). The percentage of unbudded cells at each hourly time point was comparable for all three strains, indicating that they arrested with similar kinetics (data not shown). Clb5-HAp levels in the sid2-1 strain were slightly higher than in the SID2 strain, though Clb5-HAp was not stabilized to the degree that it was upon removal of the destruction box (Figure 5A), suggesting that this defect is not sufficient to explain the arrest of sid2-1 cells.

To assay the stability of Clb2p in sid2-1 cells, CLB2ΔHA cells were arrested with α-factor as described above. In wild-type strains, Clb2p is degraded at this G1 arrest point (Amon et al. 1994). While the sid2-1 cells did not uniformly arrest at 1C as determined by FACS analysis, the profile was comparable to the SID2 strain (data not shown). Clb2-HAp was present at a slightly higher level in sid2-1 α-factor-arrested cells than in SID2 α-factor-arrested cells (Figure 5B). Clb1p/Hct1p targets Clb2p for degradation by the APC in late mitosis, and G1 cells deleted for CDH1/HCT1 show greatly increased levels of Clb2p compared to wild type (Schwab et al. 1997; see also Figure 5B). Clb2-HAp was not stabilized in sid2-1 cells to the degree that it was in cdh1Δ/hct1Δ cells. Taken together, these results suggest that while SID2 may have some role in decreasing Clb5p and Clb2p-CDK kinase activity, it is most likely very minor as Clb stability is not affected to the degree that it is by removing either the destruction box (Clb5p) or CDH1/HCT1 (Clb2p). This suggests that Sid2p is not a component of the APC and that the arrest of sid2-1 sic1Δ cells is not likely to be due primarily to a defect in APC activity (see Discussion).

sid2-1 interacts genetically with S phase cyclins: As sid2-1 sic1Δ cells had a preanaphase arrest and sid2-1 did not appear to affect APC function, we thought it likely that sid2-1 was causing a defect in DNA replication. We therefore analyzed the effects of deleting the S phase cyclins, CLB5 and CLB6, on the growth of sid2-1 sic1Δ cells. If Sic1p rescues sid2-1 by inhibiting the kinase activity of S phase cyclin-CDK complexes, then deleting these genes should mimic Sic1p expression. A deletion of CLB5 partially suppressed the growth defect of sid2-1 sic1Δ cells, and the clb5ΔΔ6 double deletion almost completely rescued sid2-1 sic1Δ cells (Figure 6, top). Deleting CLB6 alone did not have a detectable effect (data not shown). Since the removal of these S phase activators rescued the arrest caused by sid2-1 in sic1Δ cells, we hypothesized that increasing S phase cyclin levels would have the opposite effect. The destruction box of the more potent of these two cyclins, CLB5, was removed (Cross et al. 1999) and sid2-1 sic1Δ GAL1-SIC1 CLB5ΔDBΔHA strains were constructed. The CLB5ΔDBΔHA construct results in partial stabilization of Clb5-HAp (Figure 5A). sid2-1 cells that contained CLB5ΔDBΔHA showed at least a 10-fold decrease in plating.

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**Figure 5.**—Clb5p and Clb2p are only slightly stabilized in sid2-1 α-factor-arrested cells. Strains (A) MJ316 (SID2 sic1Δ GAL1-SIC1 CLB5ΔHA), MJ317 (sid2-1 sic1Δ GAL1-SIC1 CLB5ΔHA), and MJ319 (SID2 sic1Δ GAL1-SIC1 CLB5ΔDBΔHA) and (B) MJ288 (SID2 sic1Δ GAL1-SIC1 CLB2ΔHA), MJ282 (sid2-1 sic1Δ GAL1-SIC1 CLB2ΔHA), and MJ292 (clb1Δ hct1Δ sic1Δ GAL1-SIC1 CLB2ΔHA) were grown overnight to log phase and arrested with 0.1 μM α-factor for 3 hr. (A) Clb5p levels were examined at 1-hr intervals after the addition of α-factor and (B) Clb2p levels were examined before and after the arrest. The samples were processed by immunoprecipitation followed by immunoblotting.
efficiency compared to strains with wild-type Clb5 levels when grown in the absence of SIC1 (Figure 6, bottom). The CLB5 ΔBpp
c27

Figure 6.—sid2-1 interacts genetically with S phase cyclins. (Top) Strains LY986 (sid2-1 sic1Δ GAL1-SIC1), LY987 (sid2-1 sic1Δ
GAL1-SIC1), LY989 (sid2-1 sic1Δ GAL1-SIC1 clb5Δ), LY991 (sid2-1 sic1Δ GAL1-SIC1 clb5Δ cdc15Δ), LY985 (sid2-1 sic1Δ GAL1-SIC1 clb5Δ
cdc15Δ), and LY988 (sid2-1 sic1Δ GAL1-SIC1 clb5Δ cdc6Δ) were grown overnight to stationary phase in YPGal and 5 μl of 10-fold serial
dilutions were plated on YPGal andYPD and incubated for 3–4 days at 30°C. (Bottom) Strains MJ322 (sid2-1 sic1Δ GAL1-SIC1),
MJ321 (sid2-1 sic1Δ GAL1-SIC1 CLB5ΔDBpp), MJ323 (sid2-1 sic1Δ GAL1-SIC1), and MJ319 (sid2-1 sic1Δ GAL1-SIC1 CLB5ΔDBpp)
were grown and plated as described for the top.

sid2 mutants may accumulate DNA damage during replication: sic1Δ cells exhibit accelerated entry into DNA replication
presumably resulting from premature Clb5p- and Clb6p-associated Cdc28 kinase activity (Schwob et al. 1994). It is possible, therefore, that sid2
mutants would be sensitive defects occurring because of unregulated replication. This would be consistent with the preanaphase arrest observed for
the sid2-1 sic1 mutants, since DNA damage results in a checkpoint-dependent preanaphase arrest. To analyze the progression of the mutant cells in S phase, we used α-factor to synchronize the cells in G1 and monitored
DNA synthesis by FACS analysis. SID2, sid2-1, SID2 sic1Δ,
and sid2-1 sic1Δ GAL1-SIC1 strains were released from the α-factor arrest into YPD. All cells began budding and replicating their DNA at approximately the
same time, by about 40 min after the α-factor release (Figure 7). Due to the speed and partial asynchrony of DNA replication, the SID2 strains do not accumulate detectably at an intermediate stage between 1C and 2C while replicating their DNA. Only a decrease in the 1C peak and a commensurate increase in the 2C peak could be observed. At the same time intervals, however, sid2-1 cells, regardless of their SIC1 genotype, do accumulate at a
point between 1C and 2C and are delayed in reaching a completed 2C state (Figure 7). Consistent with the profiles for the sid2-1 SIC1 strain, the replication delay for sid2-1
sic1Δ GAL1-SIC1 cells is also observed when strains are released into YPGal where GAL1-SIC1 is expressed (data not shown). It may be that errors or DNA damage occur during DNA replication due to the sid2-1 mutation, since damage slows the rate of S phase progression due to a Mec1- and Rad3-dependent checkpoint (Paulovich and Hartwell 1995), and sufficient DNA damage can cause arrest with a nearly 2C DNA content.

We were interested in determining whether replication was completed in sid2-1 strains and used field inversion gel electrophoresis to probe the structure of chromosomes in sid2-21 mutant strains. Chromosomes isolated from cells blocked in replication fail to band properly on similar gel systems (Hennessy et al. 1991). This is most likely due to the presence of replication forks and bubbles, which make the chromosomes heterogeneous in size and alter their migration properties. As expected, DNA isolated from cells blocked in S phase by treatment with hydroxyurea failed to band (Figure 8, lane 9), while DNA from a wild-type strain in log phase demonstrated a characteristic chromosome banding pattern (Figure 8, lanes 1–4). Under permissive conditions, DNA isolated from a sid2-21 mutant strain migrated similarly to wild type (lane 5). In contrast, under nonpermissive conditions, the DNA isolated from the sid2-21 mutant showed much less banding than the wild-type strain (Figure 8, lanes 6–8). When taken together with the FACS analysis, these data suggest that, although the sid2-21 mutant cells may replicate most of their DNA, they still have some replication forks or bubbles present at the time of arrest. In some experiments, there was slightly more banding in the mutant at 37°C than in the hydroxyurea-treated sample. It is likely that this is either the result of a less complete arrest or the presence of fewer forks and bubbles in the sid2-21-arrested cells.

If DNA replication is slow and fails to be completed in the sid2-21 mutant strains because of the accumulation of damage, it is possible that sid2-1 mutants would be sensitive to DNA damaging agents or compounds that affect DNA replication, since then damage would be occurring for two independent reasons. sid2-1 sic1Δ GAL1-SIC1 strains were ∼100-fold more sensitive to HU treatment than sid2-1 sic1Δ GAL1-SIC1 strains (Figure 9A). A similar effect of HU was found when sid2-1 SIC1 strains were grown on
YPD, where GAL1-SIC1 was repressed (data not shown). Following UV treatment, a less dramatic decrease in plat-
Figure 8.—Chromosomes isolated from sid2-21 strains show decreased banding on an inverted field gel. Strains 1036 (SID2) and 1037 (sid2-21) were grown to early log phase in YPD. Aliquots of the cultures were removed, the cultures shifted to 37°C, and incubation continued for 6 hr. The DNA replication inhibitor HU was added to an aliquot of strain 1036 and incubated for 3 hr at 30°C. Chromosomal DNA was isolated from each sample, separated on a field inversion gel, and stained with ethidium bromide. Numbers represent the hours the sample was incubated at 37°C before chromosome isolation.

Effect of sid2-1 cells in a checkpoint pathway could also cause HU and UV sensitivity, but this is less likely because of the delay observed during DNA replication in sid2-1 strains and the cell cycle arrest phenotype observed with the sid2-1 sic1Δ strains.

To determine whether sid2 mutant cells were accumulating DNA damage and to test the hypothesis that sid2-1 sic1 cells arrest because of defects in DNA replication or repair, we analyzed sid2 rad9Δ cells. RAD9 is required for the G2 cell cycle arrest caused by DNA damage or incomplete replication (Weinert and Hartwell 1988, 1993). We constructed diploid strains heterozygous for sid2-1 and rad9Δ and homozygous for sic1Δ and GAL-SIC1. Tetrads analysis showed that sid2-1 rad9Δ spore colonies were either dead or extremely slow growing, even when GALI-SIC1 was expressed (Figure 9B and Table 3). Furthermore, analysis of the sid2-1 rad9Δ cells showed that the preanaphase Cdc-c arrest of sid2 sic1Δ cells depends on RAD9 (Table 4). The demonstration that RAD9 is required both for the full viability of sid2-1 cells and for the cell cycle arrest of sid2 Sic1Δ is consistent with the hypothesis that sid2-1 results in defects in DNA replication or repair.

DISCUSSION

Identification of genes synthetically lethal with sic1Δ:
SIC1 encodes a nonessential B-type cyclin/CDK inhibitor that functions at both the G1/S transition and the exit from mitosis. Sic1p decreases Clb5/6p-associated kinase activity at the G1/S stage in the cell cycle, delaying initiation of DNA replication. This is thought to provide the cell time to prepare properly for DNA replication (load origins, synthesize nucleotides, etc.; Tanaka et al. 1997;
TABLE 3  
rad9 sid2-1 double mutants have a defect in growth and viability

<table>
<thead>
<tr>
<th>Genotype (predicted or observed)</th>
<th>% slow growing/dead</th>
<th>% fast growing</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAD9 SID2</td>
<td>17.9 (n = 12)</td>
<td>82.1 (n = 55)</td>
</tr>
<tr>
<td>RAD9 sid2-1</td>
<td>20.0 (n = 11)</td>
<td>80.0 (n = 44)</td>
</tr>
<tr>
<td>rad9::LEU2 SID2</td>
<td>7.3 (n = 4)</td>
<td>92.7 (n = 51)</td>
</tr>
<tr>
<td>rad9::LEU2 sid2-1</td>
<td>98.5 (n = 66)</td>
<td>1.5 (n = 1)</td>
</tr>
</tbody>
</table>

Spores from a diploid strain formed by crossing rad9::LEU2 SID2 sic1::TRP1 GAL1-SIC1 and RAD9 sid2-1 sic1::TRP1 GAL1-SIC1 were dissected on YPGal and incubated at 30° for 4 days. Fast growing and slow growing phenotypes refer to colony size as can be seen in Figure 8B and were assigned before scoring sid2 or rad9. The sid2-1 genotype was assigned to viable spores on the basis of their failure to grow on YPD media.

Vallen and Cross 1999). As Clb5p/6p-Cdc28p may affect the activity of the DNA replication machinery (Duncan et al. 1999), Sic1p might also act during S phase to alter the rate of elongation. A major event in the exit from mitosis is the degradation of Clb2p. Sic1p most likely works in parallel to the destruction of Clb2p by inhibiting the kinase activity of any remaining Clb2p associated with Cdc28p. To understand more completely the regulation of these two cell cycle transitions, mutations synthetically lethal with sic1Δ were isolated. Mutations in two genes already known to interact genetically with SIC1, DBF2 and CDC15, were recovered. The products of both of these genes are thought to assist Sic1p in regulating the exit from mitosis, although their mechanisms of action are not yet completely established (Donovan et al. 1994; Jaspersen et al. 1998).

We found a novel gene, SID2, in this screen. We show that SID2 is an essential gene (see also Huang et al. 1997) encoding a protein stable throughout the cell cycle. sid2-1 sic1Δ and sid2-21p strains arrest as large-budded cells with a single nucleus, a short spindle, and DNA content that is close to 2C. This is indicative of a preanaphase arrest and is likely to be due to a defect in the preceding S phase. In contrast, cells arrested because of a failure to exit from mitosis due to high Cdc28p/Clb2p kinase activity have two separated nuclei and an extended spindle (Surana et al. 1993; Jaspersen et al. 1998). This phenotype is indeed observed with dbf2 sic1Δ double mutants (Toyn et al. 1997). sid2-1 is the only mutation currently known to be synthetically lethal with sic1Δ that causes an earlier cell cycle arrest phenotype.

Both S and M phase B-type cyclins (Clb5p and Clb2p) appear to be slightly stabilized in cells containing the sid2-1 mutation. This minor effect is unlikely to account for the sid2-1 sic1 lethal phenotype, although we cannot fully rule this out. The complete viability of sic1 CLB5ΔDB8 strains (Figure 6B) argues against the possibility that the minor effect on Clb5p stability is by itself sufficient to account for sid2-1 sic1 lethality. Similarly, the effect on Clb2p levels is minimal compared to the effect of deleting CDH1. Clb1p targets Clb2p to the APC (Schwab et al. 1997; Visintin et al. 1997; Zachariae et al. 1998a; Figure 5) but even the significant stabilization of Clb2p in cdc1 cells is not lethal. One likely possibility is that the observed stabilization of the B-type cyclins is due to DNA damage in the sid2-1 cells (Germain et al. 1997).

SID2 affects DNA replication or repair: Several arguments suggest that Sid2p acts during DNA synthesis or repair. First, the delay in completion of S phase in sid2-1 mutants and the terminal arrest phenotype of sid2-1 sic1Δ and sid2-21p cells suggest that lack of Sid2p causes defects in DNA replication or damage that blocks cell cycle progression. Second are the observed genetic interactions between sid2-1 and CLB5Δ6, which function primarily to regulate DNA replication. Third, an allele of SID2 has previously been isolated as tah11-1, which causes a temperature-sensitive growth defect in the presence of a DNA topoisomerase I mutant (top1T722A) that mimics the cytotoxic action of camptothecin (Fiorani and Bjornsti 2000; R. J. D. Reid, P. Fiorani, M. Sugawara and M.-A. Bjornsti, unpublished results). The tah11-1 mutant is also hypersensitive to hydroxyurea and to camptothecin when TOP1 is overexpressed. Other mutations that result in similar phenotypes include alleles of CDC45 and DPB11 (Reid et al. 1999). Both of these genes function in DNA replication (Araki et al. 1995; Owens et al. 1997; Zou et al. 1997; Zou and Stillman 1998) and appear to affect Oskaki fragment maturation (Reid et al. 1999). Fourth, the preanaphase arrest observed in sid2-1 sic1Δ cells is dependent on RAD9, suggesting that arrest results from induction of a checkpoint due to DNA damage and/or

TABLE 4  
rad9 sid2-1 double mutants fail to demonstrate the preanaphase arrest observed in RAD9 sid2-1 strains

<table>
<thead>
<tr>
<th>Genotype (diploid)</th>
<th>% large-budded cells with a single nucleus</th>
<th>% anucleate cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAD9 SID2</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>rad9::LEU2 SID2</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>RAD9 sid2-1</td>
<td>80</td>
<td>5</td>
</tr>
<tr>
<td>rad9::LEU2 sid2-1</td>
<td>27</td>
<td>1</td>
</tr>
</tbody>
</table>

Strains KK11 (SID2 sic1Δ GAL1-SIC1), KK17 (sid2-1 sic1Δ GAL1-SIC1), KK20 (SID2 sic1Δ GAL1-SIC1 rad9::LEU2), and KK23 (sid2-1 sic1Δ GAL1-SIC1 rad9::LEU2) were grown overnight to log phase in YPGal and dextrose was added (2%) to repress the galactose-inducible promoter making the strains sid1. The cells were fixed and processed for immunofluorescence 6 hr after the addition of dextrose. At least 200 cells were scored for each genotype. The numbers represent the percentage of cells with a given morphology. The remaining cells were those that did not have a large bud with a single nucleus. This class included unbudded cells with a single nucleus, cells with small or medium buds and a single nucleus, and cells with large buds in anaphase or telophase. Large-budded cells had buds at least two-thirds the size of the mother.
incomplete replication. Fifth, sid2-1 mutant strains are sensitive to the ribonucleotide reductase inhibitor, HU, which blocks replication progression.

One possibility is that, in sid2-1 sic1Δ cells, sid2-1 may lead to defects during S phase that are enhanced by the precocious onset of replication caused by lack of sic1. Removing the CLB5 destruction box acts to antagonize this process further by placing additional stress in what has become a critical point in the cell cycle of sid2-1 sic1 strains. Apparently, delaying either the initiation or completion of replication by GAL1-SIC1 expression or by clbΔ clbΔ provides time for sid2-1 cells to correct mistakes or to synthesize precursors required for DNA replication.

An alternative model for the role of SID2 is that it acts during the preceding G1 phase, as the cell is preparing to replicate its DNA. If sid2-1 results in the cells having not prepared properly for the forthcoming replication process, then high Clb kinase activity late in G1 may lead to lethality. High Clb kinase activity can prevent origins from becoming competent for DNA replication (Dammann et al. 1995). However, we find that sid2-1 sic1Δ and sid2-21 cells accumulate with close to a 2C complement of DNA, making it unlikely that the arrest we observe is due to a severe defect in origin firing. It is also unlikely that the early entry into DNA replication caused by sic1Δ in a sid2-1 background is lethal due to insufficient nucleotide levels. We recently demonstrated that MEC1 is required for a prereplication delay that allows the accumulation of sufficient deoxyribonucleotides for DNA synthesis (Vallen and Cross 1999). Overexpression of RNR1, the gene encoding the limiting subunit of ribonucleotide reductase, suppresses the lethality of meclΔ. However, overexpression of RNR1 does not suppress the lethality of sid2-1 sic1Δ strains (E. A. Vallen, unpublished results).

We also think it is unlikely that sid2-1 sic1Δ is lethal because of nonspecific damage to DNA. If any insult to DNA were lethal to sic1Δ cells, we would have expected to isolate many more mutations causing this phenotype. Although our screen was not saturated, there are a large number of genes whose null alleles cause increased DNA damage or faulty repair (Friedberg et al. 1991). A similar screen for mutations synthetically lethal with sic1Δ (Kramer et al. 1998) also failed to recover mutations affecting DNA repair. Furthermore, we and others have found that sic1Δ strains are not noticeably sensitive to UV or HU (M. D. Jacobson, unpublished observations; Nugroho and Mendenhall 1994) and that CLB5ΔDB and sic1Δ CLB5ΔDB strains are also not UV sensitive (M. D. Jacobson, unpublished observations). The spontaneous rate of point mutations as assayed by the frequency of canavanine-resistant colonies is also not affected by sic1Δ (K. Knox and E. A. Vallen, unpublished observations). Perhaps sid2-1 causes a very specific type of damage that is lethal in combination with sic1Δ. Whatever the defect, it is not entirely suppressed by SIC1 expression as DNA synthesis is still slowed in sid2-1 GAL-SIC1 and sid2-1 SIC1 cells and sid2-1 GAL-SIC1 cells are dependent on RAD9 for full viability.

Although fractionation experiments show the majority of Sid2p is cytoplasmic, a more indirect assay suggests the protein does contain a functional NLS, which is capable of targeting a fusion protein to the nucleus. Although we can not unequivocally rule out the possibility that the fusion protein is diffusing into the nucleus, a control fusion with the known cytoplasmic protein VirE2, which is similar in size to Sid2, failed to enter the nucleus. In addition, diffusion into the nucleus is known to occur generally only for proteins less than ~40 kD (reviewed in Kaffman and O'Shea 1999). While diffusion limits likely depend on the tertiary structure of the protein as well as its molecular weight, the Sid2-containing fusion protein is predicted to have a molecular weight of ~100 kD, making it quite unlikely that the protein can diffuse into the nucleus. Interestingly, the levels of transcription activated by the Sid2 fusion were lower than those observed for the control containing the T-antigen NLS. Consistent with the fractionation experiment, it may be that only a portion of the protein is constitutively nuclear or, alternatively, that it is transported into the nucleus during a brief period in the cell cycle. The presence of a functional NLS in Sid2 suggests that the role of the protein in DNA replication or repair, while unclear at this point, could be direct. The characterization of more sid2 alleles as well as the identification of Sid2p-interacting proteins may help illuminate the role of SID2 in DNA replication.

Cyclin-dependent kinase inhibitors have previously been demonstrated to have an important role in the maintenance of genome integrity. In mammalian cells, CDK inhibitors are induced by irradiation and are frequently mutated in human cancers, suggesting that they have a role in ensuring genome stability. Cells deleted for sic1 have an increased frequency of chromosome loss and breakage or recombination (Nugroho and Mendenhall 1994). It is likely that these defects are due in some way to advancing origin firing or DNA replication in sic1Δ cells. Identifying loci such as SID2, which genetically interact with CDK inhibitors and affect DNA replication or repair, will help elucidate the specific roles of CDK inhibitors in ensuring genome stability.

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